HYDROGEOLOGICAL INVESTIGATIONS ON THE PROBLEM OF GROUNDWATER PROTECTION IN MINING DEVELOPMENT REGIONS

Mironenko V.A., Pisanets E.P.

Leningrad Mining Institute, Department of Hydrogeology
199026, Leningrad, 21 linia, 2, USSR
Ministry of Ferrous Metallurgy, Department of Geology
103718 Moscow, Nogin sc. 2/5, USSR

ABSTRACT

Hydrogeological investigations on the problem of groundwater protection in mining areas are considered in this paper. The main processes contributing to groundwater depletion and pollution are evaluated taking into account the influence of technogenous factors.
The paper gives the analysis of the efficiency of various hydrogeological research methods aimed at estimation of the boundary conditions and the migration parameters (aquifer tests, infiltration tests, field migration tests, laboratory experiments). A combination of measures aimed at the protection and rational use of groundwater is discussed.
Certain demands are made on the hydrogeological exploration and regime observations from the point of view of groundwater protection in mining development regions.

Large-scale mining operations often result in ground-water resource depletion and deterioration of its quality over the extensive areas adjacent to quarries and mine fields. When draining a deposit, impressive water quantities - in the order of hundreds and thousands of cub m/hour - are pumped away, routinely with no constraints on their withdrawal. This causes the formation, around mine openings, of depression cones, several tens of kilometers in radius, with simultaneous head decreases measured sometimes in hundreds of meters. Coupled with aquifer dewatering, it upsets greatly the established hydrochemical equilibrium in the area. On the other hand, hydraulic-mine dumps, tailings ponds and other technical waterbodies commonly associated with mining may provide supplementary recharge sources, but also cause intensive ground-water pollution.

Whatever changes occur in the hydrodynamic situation are essentially regional in scope: the recharge areas of major water-bearing structures change their position, the infiltration recharge alters its intensity, the inter-connection between aquifers is enhanced by leakage and the entire water balance of the area in question is changed. Nowhere are these changes more obvious than in closed artesian structures where the influence of mine drainage brings usually an irreversible reduction in the ground-water resources; its more immediate cause may be either intensive draw-down of the elastic aquifer storage or gradual displacement of the contours of water body in the aquifer along the inclined impervious layers (in arid regions). In the background of these regional processes is generally a sharply expressed redistribution of the structure's dynamic storage is usually recorded between separate water-bearing complexes, depending on the position of mining cuts and drainage galleries and by the permeability of the separating strata. Such redistribution becomes a critical factor in the underground mining employing systems with roof caving, where technogenic fracturing produces a zone of greately disturbed integrity of the aquicludes above the faces.

In open water-bearing structures, changes of their hydrodynamic balance are commonly restricted to smaller areas, other conditions being equal. The key factors in such restriction are: 1. natural streams and water bodies undergoing a kind of inversion that converts them from discharge areas into recharge ones; 2. intensification of the infiltration recharge as a result of topographic changes, partial removal of the overburden and drawdown of the ground-water levels; 3. large technical water bodies feeding a steady water-balance cycle in some regions i.e. the water quantity pumped off with the drainage systems is compensated for by the infiltration from hydraulic-mine dumps and tailing ponds. In most cases, however, mining areas experience a strained water balance since the ground-water intake by the drainage systems domiates over the aquifer recharge.

On the other hand, the dewatering of mine workings, withdrawlal, purification and accumulation of mine and industrial waters set off an unavoidable change in the hydrochemical environment and break the initial (dynamic) physic-al and chemical equilibria between the constituents of the ground-water-rocks-multi-componental system. Quite often a gross deterioration in the sanitary characteristics of the affected ground water is not slow in following. In some mining areas the head decrease induced by drainage operations acts to intensify the leakage of inferior-quality waters from the adjacent horizons and squeeze mineralized pore solutions from low-permeable layers and blocks. As a whole, the hydrochemical environment in the area experiences usually an abrupt change for the worse so that, as a rule, additional and sometimes very expensive water-protection measures are needed to bring the conditions of water supply back to normal.

These occurrences convert mining areas into the earth's most sensitive "flashpoints" in terms of ground-water protection. The global scope of the problem is clearly evident from mining experiences of most countries. Among the more familiar examples are the Kursk Magnetic Anomaly, the Donets Coal Basin and the Krivoj Rog iron-ore basin in the USSR; the brown-coal areas in West Germany and the GDR; salt and iron-ore basins in BRD, USA, Canada and Australia; copper-nickel and non-ferrous ore areas in Canada, the United States and Australia. In view of their exceptional practical significance and enormous scope, coupled with a high degree of complexity, the processes listed above are being vigorously examined in many countries. In the USSR extensive research in this problem is in progress at the VSEGINGEO, VIOGEM and VNIMI Research Institutes, the Leningrad Institute of Mining and the Moscow State University. The flow of scientific papers on the subject is rapidly increasing and among the numerous works worth mentioning are those of N.I. Plotnikov (1978), V.A.Mironenko et al. (1978), 1980), J.J. Fried (1975), J.D.Waterhouse (1977), and R.E. Williams et al. (1973).

The state of the art and analysis of numerous publications on the problem lead us to the following conclusions:

1. the problem of ground-water protection in mining areas has its own clear-cut specificity caused by mining production process;

2. the problem is only solvable as long as there is close integration and mutual interfacing between the hydrodynamic and hydrochemical research methods;

3. alongside these basically new theoretical and methodological conceptions will have to be developed reaching well beyond the traditional scope of hydrogeologic investigations;

4. given the present inadequate state of the theoretical and methodological basis of ground-water protection, priority is greatly important for a thorough analysis and generalization of the observed data on the depletion and contamination of ground water in the type hydrogeologic environments;

5. to solve this problem, a fundamental revision of the design principles of drainage systems attached to mining operations is a mist; ground water, traditionally considered by miners to be a "plague of production", should be viewed as an essential mineral resource as well.

The presently available, though not very extensive, experience suggests that in practice the only way to deal with the problem is thorough effective control of ground-water resources and quality in a particular mining area; its primary goal is to find out the optimal ratios between the ground-water volumes taken up by the drainage systems and those returned into the aquifers (naturally or artificially) in the area. The concept of optimality has here to include the efficiency of a mine drainage system, concurrent with a broad use of the drainage water to supply practical needs (among them, not seldom, commercial and drinking water supplies) and the protection of ground-water quality throughout the region. But, the latter point could more siply be conceived as demanding of the minimization, as far as possible, of ground-water pollution under the selected mining and dressing technology; in reality, however, this problem, also, is essentially one of optimization because the concern for ground-water protection must be the necessary element while designing the scheme of mining workings. If so conceived, it is quite reasonable to refer to economic efficiency of ground-water protection.

With the formulated management problem in mind, the prime objectives of hydrogeologic researches in mining areas become readily apparent. They are: 1. evaluation and prediction of the hydrodynamic regime of ground water, regarding the above mentioned changes in the conditions of aquifer recharge and interaction, first of all, the recharge via the infiltration from (process water reservoirs and leakage at the sites of technogenic changes in rock permeability; 2.evaluation and prediction of the expected hydrochemical regime of ground water, should they become polluted by the water from process water reservoirs or as a result of the modified aquifers inter-connection; 3.substantiation of the necessary system of measures - active, and preventive - to assure ground-water protection from depletion and condamination and provide for the rational use or safe disposal of the water pumped by the drainage systems of mines and quarries.

1.For the first branch of investigation discussed above, emphasis has to be placed on the study of: a. boundary conditions at the outlines of rivers and natural basins, using widely for the purpose the results of observations on ground-water dynamics; b.leakage conditions which may be evaluated on the basis of aquifer tests and regime observations on ground-water dynamics, among them thermometric ones; c. technogenic permeability changes induced by rocks deformations at the sites disturbed by underground mining; d. hydrodynamic regime in the areas near process water reservoirs especially at the sites screened by low-permeable deposits. The last two tasks present more of a problem, for neither can be accomplished by the traditional research methods. For example, the methods to investigate technogenic permeability changes over underground mine workings have been adapted and utilized by only a handful of specialized research organizations. With respect to the last of the stated objectives, reliance on the standard infiltration tests, basic to these methods, has proved to be largely ineffective in evaluating the permeability of natural screens. In particular, they fail to account for the lateral water flow in stratified soils and the permeability changes subsequent to compaction under the weight of the technogenic sediments. Therefore, in practice, we should use large-scale infiltration tests with soil - moisture measurements, thermometry and inert tracers to see if and how the moisture front will migrate. These experiments bring adequate data to assess the boundary conditions of the third type at the outline of the basin and then perform the modelling of the hydrodynamic regime in its locality.

2.For the second branch, the primary concern should be directed to studying the migration parameters of the aquifers involded, as they control the intensity of mass transfer in the ground water. To do so, it is well to make use of field migration tests (FMT) in combination with laboratory experiments.

In the laboratory the migration parameters of pollutants are to be estimated for the rocks with dominating seepage through pores. Here, the findings of tests on separate samples can usually be extrapolated to rocks in situ. Beyond that, such experiments may be helpful also in mass tranfer studies on fissure porous rocks. Clear-cut distinction are to be made between the experimental procedure designed for high- and low-permeable (clayey) soils; particularly in the specification of boundary conditions. An important though still debatable question concerns the methods for laboratory estimation of sorption parameters. Whereas most authors are strongly in favour of dynamic trials the errors inherent in the intensified experimental schedule are oftentimes so large as to make the findings of static experiments far more preferrable. Estimation of mass transfer parameters runs into serious difficulties when unsaturated conditions are met with, still more when the heterogenous structure (double porosity) of a sample have to be taken into account.

In the field, aquifer migration parameters are derived from FMT's based on tracer applications. The FMT filtration pattern underlies their categorization into those in natural and disturbed flows. Of these the latter trials are the more reliable, following the scheme from the tracer injection into the central well to the subsequent inspection of its distribution about the stratum via observation wells; trials patterned on the "doublet" scheme are less frequent but very effective.

The inevitable impact of scale effects, owing to the limited areal dimension and short duration of mass transfer in experiments, makes it necessary to discuss expedient limits of FMT applications with respect to different rock complexes (Mironenko et al., 1980). The distinction of experimental conditions is most clearcut for porous rock complexes vis-a-vis significantly fractured rocks. The principal consideration here centers on differences in storage properties and actual water velocities, as well as the possibility to preserve the structures of water-bearing rocks in laboratory experiments. If applied to porous (sandy-clayey) rock complexes, FMT's are either ineffective or fail to offer tangible advantages over laboratory experiments. By contrast, no other alternative exists for field FMT's in fractured rocks. And because ground-water contamination is generally found to be most intensive in essentially fractured rock complexes, FMT's have to be made part of the standard set of hydrogeologic exploration techniques in all sites where it is necessary to guarantee ground-water in fractured reservoirs from pollution.

So far the experience with tracer sampling tests has been heavily limited - the fact necessitating their thorough planning, consistent with the stages and details of hydrogeologic exploration programs. An extremely valuable and useful adjunct to the data of laboratory determinations, if the experiments are to be effectively planned and carried through, is found in hydrogeophysical studies in test wells involving flow-rate measurements and especially resistivity logging (or thermometry). This is all the more valid inasmuch as the FMT performance pattern is governed by the degree of vertical differetiation in rocks filtration properties and water composition. With this in mind, closer attention is paid to the design characteristics of the test wells so as to minimize the likelihood of various casual fluid leakages.

Little is known as yet about migration tests as applied to rocks in the aeration zone. Realistically, one can count presently on experimental determination of mass transfer parameters for high level moisture in the tested rocks during the experiment. Since the only way to control the tracer tests in the unsaturated zone relies on monitoring the chemical status by the rock samples taken for the purpose of squeezing pore water, so the generally accepted calculation proceedures need a revision.

A separate field for experimental investigations is connected with studies of behaviour of various chemical components as they are co-disposed into water-bearing complexes with liquid wastes, with principal attention to probable self-purification of ground-water. Here, consideration have to be given to the changes of the physical and chemical state caused by the mixing of water of different chemical composition, the pattern of oxidation-reduction processes, disruption of the gaseous status of aquifers and other relevant factors. On the other hand, deep aquifer drainage propels the saline water and brines to the surface whose disposal or utilization develops into an independent problem which also requires special experimentation to identify remedial action. Lastly, research efforts to reveal natural tracers, or labels, providing reliable diagnostic clues to the degree of inter-connection between surface and ground water in the areas of potential pollution, are very important.

The hydrogeologic parameters arrived at in experiment provide basic inputs for forecasting the processes leading to ground water contamination and depletion. The most effective way for prognostic estimation of the processes is mathematical modelling and particularly numerical one. E.G. in dealing with the problem of ground-water protection in mining areas, numerical modelling is applicable for: a. justification of physical transport models; b. justification of computation model (migrational schematization); c.forecast of contaminant distribution in ground water and substantiation of the sanitary protection zones in the vicinity of water intakes; d. planning and interpretation of field migration tests and regime observations on hydrogeochemical trends. A special note is in order here that the numerical slution of the mass-transport problems demands an approach basically and substantially different from the tried and tested methods accepted for modelling of the geofiltration problems.

3. Results of the research programs completed to date provide a starting ground for control of ground-water resources and quality and designation of effective engineering measures - both through active intervention, control and prevention. E.g. resource control can be achieved by varying the degree of screening of process water basins through the installation of artificial screens, purposeful hydraulic filling of low-permeable "tails" etc. Supplementary artificial resource replenishment may be developed through the transfer of the surface flood runoff into a subsurface runoff or through the secondary discharge of pumped mine water via special infiltration pools and bore holes; in particular, injection wells can be used to put up a "hydraulic barrage" as a means to elimination the spreading of the piezometric cone in the area of a quarry (mine) field.

The foregoing measures, seeking to achieve hydrodynamic purposes, produce naturally a large regulating effect on ground-water quality as well. Aside from them, control of the contamination processes implies also a comprehensive appraisal of the water's capacity to self-purification as it filtrates through rocks, owing to sorption effects, ion exchange, destruction of unstable compounds in the long process of transport, and other factors. Control of self-purification is likely to consist of sensible vertical differentiation of the infiltration flow velocities (the rate of water intake) plus artificial redistribution of the flow rate among the constituents of the water-bearing system (e.g. outfitting of drainage wells with appropriate filter designs or provision of water-level depressions excluding of a direct water inflow from the rock complexes having poor "cleaning" characteristics). Finally, water quality control proceeds by maintaining a desired composition of industrial effluents in their storage basins - through the precipitation of salts, sedimentation of suspended material, stimulating of the sorption processes on technogeneous sediments, and other techniques.

The attentive examination of possibility of the drainage water use for the purpose of water supply is necessary for the effective control of ground-water resources and quality in mining areas. Moreover, experience has demonstrated the use of drainage water to have a large potential for provision of drinking water in some areas. The most stringent constraints on it are imposed, besides the chemical composition of the pumped water, by the demand for sanitary protection of the water-intake drainages. Yet the analysis has shown that suggesting this demand may be satisfied even in areas mine workings and surface constructions are present within the sanitary protection zone. This alternative is viable of course as long as the "buffer" properties of the aeration - zone rocks have been subjected to close scrutiny and that, in turn, calls for a preliminary investigation of the mass transfer processes in unsaturated media, its technology remaining very poorly developed for the time being.

One of the important elements of the ground-water resource and quality control is a regime observation network of hydrological wells, to be arranged directly in the quarry (mine) field and beyond.

Demands on the lay-out of the regime networks installed at ground-water contamination sites will diverge significantly as dictated by hydrodynamic vis-a-vis hydrochemical considerations. E.g. in the water-bearing complexes having commonly high filtration velocities and appreciable dispersive properties (in particular, fissure rock somplexes) the observation data as coming from the wells situated near the source of pollution do not allow an accurate estimation of the transport pattern, more so because the vertical hydrochemical differentiation is most pronounced here. From the standpoint of evaluating the self-purification processes or dispersion effects it is clear that the primary interest will focus on the wells located within the transition zone. As a result, the closely spaced observation wells, soon to be found beyond the contamination front, supply very poor hydrochemical information. The predicament is further aggravated in view of the increased filtration velocities that normally take place near the source of pollution, while the parameters of the filtration medium here are often in no way indicative of the mass transfer zone as a whole.

Because of the profile filtrative non-uniformity and gravitational differentiation (yet another important factor) the major bulk of the contaminants is often seen to be spreading only within some aquifer zone of limited thickness. Even for comparatively large values of the transverse dispersion coefficient the areal extension of such sites of a non-uniform hydrochemical profile may well be measuring in hundreds of meters or kilometers. For this reason, the samples derived from the wells whose screens either find themselves outside the zones of the dominant type of pollution or, conversely, significantly surpass them in thickness, fail to be representative here. Hence the need arises for the stratum to be screened at short intervals of its entire thickness, but this is in conflict with the significantly less rigid demands on the hydrodynamical observations by piezometers in conditions of planar filtration.

On the whole, design of an observation network in areas of probable ground-water pollution from industrial liquid-waste basins presents a complex optimization problem hard to resolve unless anticipated by preliminary exploratory modelling. Later on, with integration of the information concerning the initial stages of contaminant proliferation, a mathematical model is used to perform the adjustment of the observation network and to plan for its further growth. It is also desirable to bring observation wells into operation one-by-one, as observation data begin to multiply.

The foregoing implies that among the future branches of research in the problem of protection and rational use of ground water the areas of emphasis are: 1.improvement of the methods to estimate the infiltration losses from the industrial liquid waste basins; 2.development of the methods to evaluate and to forecast changes of hydrodynamic conditions in the areas of underground mineral development and production by systems involving roof caveing; 3. updating the methodology for the justification of the sanitary protection zones attached to water-intake drainages; 4. formulation of the demands on the arrangement and carrying out of observations at ground-water contamination sites; 5.perfection of the numerical modelling techniques to forecast ground-water contamination. Lastly, among the first priority goals, reference must be made to the development of special requirements to hydrogeologic exploration of mineral deposits, incorporating the need for effective control of the ground-water protection problem within the region of current development. With these requirements being fulfilled, reliable initial data can be assured and long-term forecasts developed regarding changes of not only hydrodynamic, but also hydrochemical conditions in the regions of mining. Ultimately, this will make it possible to evaluate adverse influence of mining upon ground-water quality, so the measures towards their protection to be substantiated. Naturally, primary attention in the areas of exploration is to be paid to field migration tests.

In planning hydrogeological exploration, certain difficulties are bound to stem not only from the need to transfer new methods into routine hydrogeological surveys, but also and to a large extent, from changes in the standard methodology. As previously noted, the informative value of the investigations at the sites of industrial liquid-waste disposal must be enhanced and geofiltration aquifer testing is in need of major corrections. This is because the reliability of prognostic estimations with respect to the ground-water contamination processes is hinged largely on the degree of accuracy accepted for the lithological and structural, filtration differentiation of the water-bearing complexes. Specifically, the danger of regional aquifer pollution will be controlled primarily be the presence of increased permeability zones in the profile. However, pumping tests (in the standard variants) are unable to evaluate anything but the total hydraulic conductivity of the stratum, thus averaging - and for good reason, as long as the filtration calculations are the case in point - the parameters of the filtering stratum in the profile; yet such an approach most often appears much too crude to be acceptable from the viewpoint of the subsequent migrational schematization.

The necessary degree of differentiation of the filtering profile may be sometimes attained by using the short separate pumping intervals, but as a rule this measure making the cost of the exploration programs a deal more expensive, will not make certain the required quality of the output data. It seems therefore more effective to incorporate tracer injections as a routine method in the pumping tests, together with widescale application of the hydrogeophysical techniques.

On the other hand, field aquifer tests, in their current modification, fail to supply data on the permeability of the sediments across the bedding, and this excludes the identification of this essential parameter from current exploration practice. Nevertheless this parameter is broadly responsible for the specific differentiation pattern of industrial effuents at their entry into the aquifers. It is also a critical parameter in evaluating the "inflow" of deep mineralized water at the sites of intensive upper aquifers drainage (as part of the effort towards dewatering mineral deposits). Hence new requirements to the experimental procedures become clearly evident.

In light of the foregoing, future success of hydrogeological exploration will be largely dependent on whether the usage of hydrogeophysical methods will be broad enough. The latter can both have the independent purposes as e.g. in the layer-by-layer estimation of the filtration flow velocities at separate sites, and have also ancillary value in contributing to a higher informativeness of other types of work, like field migration tests.

CONCLUSIONS

The key conditions for successful progress of future research on the problem and for effective application of the reviewed principles for the control of ground-water resources and quality in mining areas are: 1.integrated character of exploration and design attained for the parallel solution of the problems of mine workings drainage and ground-water protection, and premised on the integration of research branches which are significantly divorced in hydrogeology by a long-termed tradition; 2. broad use of the adaptive approach based on gradual refinement of the calculation models through the data acquisition with the progress of the exploration, construction and operation of mines; 3. analysis and scientific generalization of the data concerning representative locations where reliable parameters of migration and filtration have been found during mining operation, through the solution of the corresponding inverse problems. The latter two aspects are considered specially important also, because the study of the problem in question has to rely broadly on the ideas and methods largely untested in practice and which extend far beyond the limits of the standard hydrogeological investigations. Nevertheless, the experience now available from investigations in several major mining areas [1] brings incontrovertible evidence of the economic efficiency and large future potential of the integrated approach outlined here.

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1) Perhaps the most comprehensive description of experience of this type may be found in the monograph of V.A.Mironenko, V.G.Rumynin and B.K.Uchaev (1980).

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