SUCCESSES AND FAILURES IN PREDICTION OF GROUNDWATER REBOUND IN ABANDONED MINES - SOME THEORY AND CASE STUDIES

Miran Veselič [1] and Peter J. Norton[2]

[1] IRGO - Institute for Mining, Geotechnology and Environment, Slovenčeva 93, 1000 Ljubljana, Slovenia. Telephone +386 61 346 690, Fax +386 61 341 680, E-mail: miran.veselic@i-rgo.si.
[2] Peter J Norton Associates, 10 St Nicholas Close, Richmond, N. Yorkshire, DL10 7SP, UK. Telephone +44 1748 825111, Fax +44 1748 850395.

Abstract

Due to environmental and political factors many mines are closing, the pumps switched off and groundwater rising through the abandoned workings. The Kyoto summit meeting in December 1997 to tighten emission controls will have a severe impact on the coal mining industry and many more mines are expected to close. It is important therefore to be able to predict the impact of the groundwater rebound on the surrounding environment and to assess the economic and sometimes the social effects of this phenomenon.

The authors have chosen some salutary examples from their worldwide experience to show the problems associated with predicting the rate of groundwater rebound and the potential for river pollution, flooding, subsidence, gas migration, surface instability and other geotechnical problems.

The authors provide an up to date approach to groundwater rebound phenomena and place the subject in perspective with other mine closure effect. They show that it is dependant on the hydrogeological technical and operational features of the mine itself and its past dewatering history. The reader is reminded thet there is no such thing as a standard mine or aquifer and that given the diversity of the environment and the frequend lack of appropriate data then prognoses are sometimes difficult and must be based on experience. Because of this errors are made that must be honestly acknowledged and accounted for. Some case studies are presented and it is considered that the best prognosis of the effect on mine closure will come from projects where is situ short term groundwater rebound tests can be accomplished. Where this is not possible then careful and continous groundwater monitoring is recommended.

INTRODUCTION

Mine closure is an indispensable part of the mines' life. As active mines usually develop a specific social environment and structure, a mine's closure is a socially very itching process. Nevertheless, mines affect also the environmental tissue of their surroundings. At least in the developed countries, this tissue, both visible and non visible, has become a matter of public concern in all phases of mine life. From its planning to its closure, this is adding considerable external costs to the mining activity. Linked to the higher labour costs and depleted resources, this is raising raw materials production costs and making mine closure an everyday concern within these countries. Environmental effects, resulting from mine and post mine closure have therefore become an important topic both from geo-scientific and technical points of view.

Surface and ground waters are important constituent of the environment. With ever growing water needs and shortages their practical importance is gaining momentum. Groundwater related environmental effects of the mine and post mine closure processes must therefore receive due consideration. If being environmentally adverse, they have to be reduced if not eliminated by some appropriate action.

Most of the active mines operate below the local groundwater level and therefore affect local or even regional groundwater flow conditions. Generally, this is affecting the groundwater level, its flow direction, its water quality and as a result, its availability. Even when not operating below the local groundwater level, the mines may still affect groundwater. They do it by the effluents of their ore concentrating facilities or simply by modifying the extent and the quality of the local aquifer recharge from precipitation.

To the non mining public, mine closure might seem just an end of a lasting nuisance and a simple reversal of the mine opening and development processes. Yet, a mine impact to the Geosfere is a lasting and an irreversible one. Mineral excavation has created surface pits. Possibly, they have backfilled them by poorly consolidated fractured rock and rock debris. It has created lasting subsurface voids from mine openings and subsequent caving in, rocks fracturing and subsidence. Voids induced into the rock masses by excavation and subsequent rock fracturing have opened new surfaces to the ore mineral's hydration and oxidation processes. Unless at least locally blocked, they are after mine flooding the new, highly conductive artificial groundwater conduits. Functioning similar to karst channels in karst aquifers, they form new aquifer drainage and privileged groundwater flow pathways, substantially modifying the aquifer's original intrinsic flow pattern. Eventually, they may reverse the original inter-aquifer flow between the affected aquifers.

When mining deep under the local groundwater level required great local aquifer depressurization and water level lowering, groundwater rebound is the most obvious and dramatic of all the mine closure environmental effects. After the stop of a mine dewatering facilities, groundwater may rebound for hundreds of metres. It may reach levels, unknown to local population for decades or even for centuries. It may recreate springs and marshlands, rewater old dry creeks or kill the flourishing life within the existing ones. Yet, as it comes, groundwater rebound is not a matter of solely environmental concern. The water may flood the mine before the mine company could properly evacuate it. It may promote open pit backfill or caved-in overburden consolidation and surface subsidence. Rebounding water may add critical buoyancy effect to the already meta-stable surface or subsurface rock masses or to the strata, destabilized by the roof caving and subsidence. Further, it may dissolve soluble strata, wash out tender sediments or leach landfills and backfills, provoking not only pollution and aggressiveness of water but also uncontrolled subsidence. All this may endanger the old and the newly built surface structures and settlements. Therefore, it is of vital technical and environmental interest to make as good as possible groundwater rebound prognoses. Any substantial discrepancies may lead to wrong decisions and to potential damage and related financial losses. They already did and they still may lead to the legal claims and disputes.

MINES AND THEIR HYDROGEOLOGIC ENVIRONMENT

Mined mineral substances may just impregnate certain volumes of host rock, form up massive ore veins, lenses or layers, or even lithologic seams or strata. According to this, they may occur in rocks or form strata that are aquifers in strict hydrogeologic terms. They may also occur in rocks or form strata considered as water bearing or aquifers by miners, but as just semipervious or even very poorly pervious (aquicludes, magazine rocks) by hydrogeologists. They may, finally, occur in rocks or form strata classified by both miners and hydrogeologists as impervious (aquifobs).

Strata containing mineral substances may attain regional extension (i.e. coal, copper). Such strata or host rocks may lie next to the rocks corresponding to one of the above three hydrogeologic rock categories. In miners terms these adjacent rocks may form a foot wall or bottom wall, hanging wall or overburden and sidewall or lateral strata. By their mine dewatering function we classify them as aquifers, or as barriers and safety pillars. Each of these may lie directly next to the ore body, or may be separated from the later by another type of rock or strata. Usually, the involved aquifers and water bearing rocks are part of the regional groundwater flow.

With underground mining, the extraction of a mineral substance induces fracturing and caving in of the ore body's host rock or stratum and of its overburden. With some mines, fracturing may to some extent affect even its bottom wall and sidewalls. All this creates a considerable amount of induced void space. To reduce caving in, rock fracturing and surface subsidence, underground mine workings are backfilled and a small amount of void space remains. Nevertheless, with soft rocks and great overburden stresses, minerals' excavation may as well provoke just rocks' plastic deformation and re consolidation. This leads to closure or reductions of unsupported mine openings and no residual fracturing at all.

With surface mining, the extraction of a mineral substance involves excavation and redeposition of the overburden strata. They generally backfill these within the open pit itself, representing poorly consolidated landfills.

Mines can be just individual mines or pits, or they may form groups of interconnected mines or pits, eventually mine fields (i.e. coal fields) of clear regional extension. They may, therefore, very much vary with respect to their internal structure and extension and be part of very different natural hydrogeologic environments, the later potentially modified by mining itself. Further, they can exist in very different climatic and hydrological conditions. These largely influence dewatering measures and costs, and affect both the rate and the extension of groundwater rebound.

To summarize, with respect to hydrogeologic structure in which they occur and may be qualitatively altering, we can divide the mines into the following groups:

1. mines within a virtually unlimited aquifer or water bearing rock,
2. mines within a limited or compartmented aquifer or water bearing rock,
3. mines interconnecting several limited and/or unlimited aquifers or water bearing rocks,
4. mines next to a virtually unlimited aquifer or water bearing rock,
5. mines next to limited or compartmented aquifers or water bearing rock,
6. mines forming primary water bearing structures within poorly permeable strata.

With respect to their hydrodynamic nature, the involved aquifers and water bearing rocks can be within a mine reach either:

- confined; with lateral or bottom groundwater inflow only,
- unconfined; with inflow from precipitation or surface waters and, generally, also with lateral or bottom groundwater inflow.

EFFECTS OF DEWATERING

The extent and characteristics of actual and past dewatering are very much dependant on the mine's position within the hydrogeologic structure.

Mines in aquifers or water bearing rocks, previously defined as types 1, 2 or 3, develop within these aquifers cones of depression that depend on:

- the mine bottom excavation and dewatering levels,
- the mine workings' extension,
- the aquifer relative position within the hydrogeologic structure (basement level),
- the aquifer geometry (thickness, lateral extent; spacial variability),
- the aquifer porosity (intergranular, fracture, channel or karst)
- the aquifer hydrodynamic parameters (permeability or transmisivity, storage),
- the aquifer anisotropy and heterogeneity, including compartmenting,
- the aquifer original dynamic or "static" level,
- the aquifer hydrodynamic confinement, and,
- the aquifer's recharge.

An underground mine is functioning within the affected hydrogeologic structure as a great uneven drainage well. Parameters governing its dewatering function are extension of mine workings and bottom dewatering level. It is draining the individual aquifers or parts of a heterogeneous, stratified and compartmented aquifer according to their relative position within this structure and due to their hydrogeologic features and corresponding working depression. In the later, separate water inflows onto the upper mine levels may persist, though maximum water inflows generally occur at the lowest or the mine dewatering level. Where fractured overburden rocks within the subsidence area of the past mineral excavation act as infiltration area for surface precipitation or drainage area for some overburden aquifers, the resulting inflows are independent of the mine dewatering level and must be calculated accordingly. With surface mines, a definition of the acting extension of mine workings must take into account also backfilling of the open pit and formation of an unconfined aquifer within such back or landfill.

Mines situated next to aquifers or water bearing rocks, previously defined as types 4 or 5, do not directly affect aquifers by the total extent of their workings. Only in cases where underground mining requires active dewatering of some adjacent aquifers, conditions for these aquifers do not differ from the previous ones. When passive or a combination of passive and active protection of the mine against some or all of the adjacent aquifers is sufficient, then the situation is very different. The total extension of the workings replaces extension of the mine requiring an aquifer depressurization and its maximum allowable water level substitutes the aquifer's basement level. Within such aquifers is the cone of depression reduced and has no direct relation with the mines bottom working and dewatering levels. However, no significant difference exists with the previous types of mines as much as the impacts of overburden caving and fracturing are considered. For surface mines, the effects of passive and of combined passive and active protection are very much similar to those just discussed. The backfills related remarks, given above for the previous mine types, relate also to these surface mines.

Mines forming primary water bearing structures within poorly permeable strata, previously defined as type 6, act as a drainage system receiving water from the surrounding rock. They relate the extent of dewatering and locations of the inflow to the structural disturbances, providing the poorly pervious strata with some permeability. The bottom mine working and dewatering level and mine workings lateral extension do not control individual inflows. However, they generally control the total mine inflow.

Interconnected mines or groups of mines may occur in any of the above mine types. They involve regional aquifer dewatering with local groundwater drawdowns corresponding to dewatering levels of the individual mines.

According to the extent of past dewatering, the aquifers and water bearing rocks may either be:

- depressurized, but saturated due to remained water pressure or capillarity,
- dewatered or drained and so essentially dry.

Dewatered and essentially dry rocks lie above the dynamic water levels within the cone of depression area. The unit volume of drained voids depend on the effective porosity and therefore on the nature of the rock. Large differences exist between rocks with this respect. Effective porosity may be up to an order of ten percent in unconsolidated rocks with intergranular porosity, of the order of some percent in consolidated rocks with intergranular porosity, and of the order of much less than one thousandth with some poorly permeable fissured rocks. It is usually not measured during the mine dewatering and must be deduced from other studies 3 . It may be deduced from specific yield values of the unconfined aquifers, but must not be mistaken for storage or storativity of the involved undrained confined aquifers. Yet, the rock effective porosity alone is not enough. In order to access the total drained void volume, the shape and the extent of any individual involved aquifer as well as the shape and extent of its cone of depression should be known. This is why we agree with the referenced authors which consider the estimation of the total void volume of dewatered rocks or water capacity of rock massive as generally difficult 2 and bound to errors 2,3 . This errors may be particularly important in cases of mines situated within the very large and water yielding karst aquifers, tending to be compartmented and stratified, and where the true shape of the cone of depression is hard to define.

GROUNDWATER REBOUND PREDICTION

The mine workings within a single mine constitute a well connected structure. This is less intense in the case of connected mines 2 or mine fields 3 . But even in the case of physically not connected mines, draining the same aquifer, the mutual dewatering influences should not be overlooked or ruled out 3,6,7 . When treating mine drainage problems, the mutual influences of a group of mines must be considered. It is even more so when treating the groundwater rebound after the mine flooding. As indicated by Rogoz 2 , flooding of a connected mine could overdue the pumping capacity of the other, thus leading to the premature flooding of both. But even in the case of possibly unconnected coalfields, as indicated by Sherwood&Younger 3 , might the flooding of one coalfield provoke excessive groundwater rebound and subsequent environmental damage within another coalfield, mining the same coal measures.

Though conceptually the same, we feel that the approach to the rebound prediction for a single mine 6,7,9 , or for a few more or less simultaneously rebounding connected mines 2 , has to be separated from the approach to regional groundwater rebound predictions, as applied in the case of the closure of a series of coal fields 3 . In the first case, the construction of a reliable numerical model would be very time consuming and not feasible 2 , but the problems can be mastered by relatively simple algorithms 2,3,6,7,9 . In the second case, however, regional problems can not be solved without some sort of numerical model, let it be a deterministic groundwater model or a probabilistic lumped parameter model as the one based on Monte Carlo simulation 3 .

For the sake of simplicity, we will in our further theoretical discussion concentrate our effort to the groundwater rebound within a single mine. Later, we will try to draw parallels and comment on the more complicated cases.

Conceptually, the groundwater rebound is a simple phenomenon, dependant on just two parameters:

- the void volume to be filled up with water within the mine and the dewatered parts of the aquifer or water bearing rocks, and,

• the water inflow to fill the dewatered void volumes.

It can be assimilated to any "budgetary" problem, where "expenditures" have to be matched by "incomes". Unfortunately, one knows that as simple as the budgetary problems may be, they are never simple to solve. And so is with the groundwater rebound.

Nature of void volumes

The total void volume of a mine to be filled with inflowing water is consisting of the following partial void volumes:

- volume of the permanent and open mine shafts, inclines, galleries, roadways, rooms and caverns,
- unconsolidated backfill pore volume of the backfilled supported mine shafts, inclines, galleries and roadways,
- consolidated or unconsolidated backfill pore volume of the backfilled poorly supported mine inclines, galleries and roadways,
- consolidated or unconsolidated backfill pore volume of the backfilled long walls, rooms, caverns and other underground mine workings,
- pore volume of the consolidated caved in rock material within long walls and other underground mine workings exploited by caving in or similar mining techniques,
- consolidated pore volume of the backfill or landfill, in the case of open pit mines.

In order to properly access the above data, the information on the nature and initial volumes of the mine workings are needed, as well as the data on the extent and nature of the caving in process and on the extent of subsequent surface subsidence and on the nature and initial porosity of the backfill material. The initial porosities of the later may lie between 30% (water driven backfill) or 0% (backfill concrete). We have found the porosities of consolidated water driven dolomite material backfills in a coal mine to be of the order of 10-15%. The porosities of partly consolidated caved in soft rock claystones and marlstones were of the order of 1-5%. As follows from our above explanation, the available or spare void volume within the mine is less than the original volume of the mine workings and of the worked out seam. This was for coal mines already stated by Rogoz 1,2 , who defined the residual mine voids as "water capacity of the goaf" and the reduction ratio as "coefficient of water capacity of the goaf". It is important to note that even in a case, when the subsequent caving in process has fractured the overburden rocks up to the surface and provoked subsidence, the remaining total void volume can not be but a fraction of the volume difference between the volume of the subsidence and the volume of the originally extracted mineral substance.

From the above discussion and from what has been previously said on the assessment of the flooding prone or available water bearing rock or aquifer void volume (i.e."water capacity of goaf and the rock mass" as defined by Rogoz 1,2), we can deduce, that a good estimate of the total available void volume is far from being easy. Moreover, in order to use the available total void volume data in mine flooding prognoses, they must be elaborated for the appropriate mine level or flooding depth intervals. We may further conclude, that in complicated structural settings, more uncertainty is to be expected in determination of the available void volume in the water bearing rocks or aquifers than that of the past extracted volumes of the mineral substance. Therefore, the uncertainty of the estimate of the total void volume available for flooding will be generally greater for the mines within the aquifer (previously defined mine types 1, 2 and 3), and smallest for the mines forming primary water bearing structure within a poorly permeable strata (mine type 6).

Estimate of water inflow

Inflow to the mine at a certain point is a function of the original aquifer dynamic or "static" water level and of either the bottom wall level of the affected inflowing aquifer (cases of "hanging" aquifer inflows) or the lowest mine workings or active dewatering level of the mine when the bottom wall of the aquifer being deeper (cases of "partially penetrating mine" inflow). The affected aquifers may be either confined or unconfined or free water table. As previously stated, additional inflow may result from infiltrated precipitation or from old man and is independent from the active dewatering level.

In the case of a single affected aquifer, regardless of his eventual heterogeneity or compartmenting, the following equations can be stated to estimate the water inflow rate Q into a mine as a function of the active mine dewatering level h and "static" water level H or acting drawdown s, and by taking into account the infiltration inflow Q_i 6,7 :

confined aquifer: $$Q = C_c*(H-h) + Q_i = C_c*s + Q_i \qquad (1)$$

unconfined aquifer: $$Q = C_u*(H_2 - h^2) + Q_i = C_u*(2*H-s)+Qi \qquad (2)$$

It was shown that the differences in inflow versus drawdown estimates between the above two equations were in the practical cases insignificant, so we recommend the use of the first equation. We may define water inflow rate to the mine from the aquifer as Q_a, and link it to the total mine inflow or mine water discharge rate Q and infiltration or fractured overburden inflow Q_i, with relation $Q_a = Q - Q_i$. We can then for practical cases, where we dispose only of data on total mine discharge Q and infiltration and fractured overburden inflow Q_i, define the later difference as a function of inflow level h, or, still better, drawdown s only:

single aquifer discharge case: $$Q - Q_i = C_c * (H - h) = C_c * s \qquad (3)$$

In the case of two mines dewatering the same aquifer, their mutual influence can be estimated by the simple equations 6,7 given below. According to the above conclusion on the general applicability of the equation (1) they are based on this equation. Symbols are as previous, with $B_{i,k}$ being the parameter of mutual influence of the two mines:

drawdown in mine 1: $$s_1 = Q_1 / C_{c1} + B_{\{1,2\}} * Q_1 / C_1 \qquad (4)$$

drawdown in mine 2: $$s_2 = Q_2 / C_2 + B_{\{2,1\}} * Q_2 / C_2 \qquad (5)$$

After determining values for parameter C_c for each mine from the data on past dewatering records, it is easy to determine from the same records the $B_{i,k}$ parameter values for both mines and estimate their mutual influences subsequently.

For a mine interconnecting several confined or unconfined aquifers, or draining a very heterogeneous, stratified and compartmented aquifer, which is resulting in a series of "hanging" aquifer inflows in roadways and mine workings at different mine levels, the corresponding simple equations have been advanced by Rogoz 2 . As well as the previous formulas they may be used in computer simulation of the mine inflow during mine flooding, provided that the necessary data are available from the past mine dewatering records. For N registered inflows into the mine with i (1...N), the initial inflow level and inflow rate of i - th inflow are h_{oi} and Q_{oi} respectively. With active mine dewatering (or mine flooding) level being h, the total discharge into the mine at that level is Q_h and the i - th inflow rate is Q_{hi}. With symbol for "static" water level being H as previously, the following relations can be advanced after Rogoz [2]:

total inflow into the mine: $$Q_h = \Sigma Q_{hi} \qquad (6)$$

i - th inflow rate for $h > h_{oi}$: $$Q_{hi} = \frac{H - h}{H - h_{oi}} * Q_{oi} \qquad (7)$$

i - th inflow rate for $h \; h_{oi}$: $$Q_{hi} = Q_{oi} \qquad (8)$$

The authors do not pretend that the above simple formulas may substitute the elaborated numerical groundwater models. Unfortunately, much too often is the structural setting in which the mines are operating very complicated and the hydrogeological and dewatering data not adequate for the purpose. In such cases simple estimates are better than models based on lack of data. Or, to illustrate it with a quote from Rogoz [2]: "taking into account the numerous potential inaccuracies of the input data and the simplicity of the hydraulic model, the error in determination of H ("static" level!) will have a small influence on the accuracy and credibility of the results".

Rebound prediction

To illustrate the problems encountered when engaging for a rebound prognostic, let us quote two other valuable authors, Sherwood& Younger [3]: "Paradoxically efforts to predict rate and spacial variation in groundwater rebound after coalfield closure are hindered by both the lack and superabundance of various kinds of data. There is generally lack of suitable hydrogeological records, largely because the methods of groundwater investigation most suited to solution of operational problems during mining operation are not well suited to providing the classic hydraulic parameters needed in groundwater models. This is compounded by the frequent mismatch between the definitions of such parameters and the hydrogeologically non-standard nature of underground workings"

It is therefore sound to go back to our simple algorithms of the single mine groundwater rebound prediction case and try to formulate the involved void volumes. If we attribute V_t to total void volume of the mine workings and dewatered rocks, V_m to the total void volume of the mine workings or goaf, V_o to the total void volume of the persistent mine openings, V_b to the total void volume of backfilled mine openings, V_c to the total void volume of the involved caved in fractured rocks and V_r to the total void volume of dewatered rock masses or aquifer, we can define the following relations:

total available void volume: $$V_t = V_m + V_r \qquad (9)$$

total mine volume: $$V_m = V_o + V_b + V_c \qquad (10)$$

For every of the above volume categories we may define respective area A and respective effective porosity n_e, with porosity of mine openings n_{eo} being 1. By using the above introduced subscripts and introducing h for height above a certain datum level within the mine, and h_j and h_{j-1} for a pair of such successive height levels, we can define the following set of relations:

V_o between levels h_j and h_{j+1}: $$V_o = A_o * n_{eo} * (h_{\{j+1\}} - h_j) \quad (11)$$

V_b between levels h_j and h_{j+1}: $$V_b = A_b * n_{eb} * (h_{\{j+1\}} - h_j) \quad (12)$$

V_c between levels h_j and h_{j+1}: $$V_c = A_c * n_{ec} * (h_{\{j+1\}} - h_j) \quad (13)$$

V_r between levels h_j and h_{j+1}: $$V_r = A_r * n_{er} * (h_{\{j+1\}} - h_j) \quad (14)$$

Applying again the symbols and the notation used with the water inflow algorithms, we can further define the mean mine inflow $Q_{j,j+1}$ related to active mine dewatering levels (or mine flooding levels) h_j and h_{j+1} with the following relation:

$Q_{j,j+1}$ related to levels h_j and h_{j+1}: $$Q_{j,j+1} = C_c * \left(H - \frac{1}{2} * (h_j - h_{j+1})\right) + Q_i \quad (15)$$

Similarly, taking into account that drawdown s is the difference between the "static" level H and the active mine dewatering level h, the mean mine inflow $Q_{j,j+1}$ between the drawdown levels j and $j+1$ is given with the following relation:

$Q_{j,j+1}$ for drawdowns s_j and s_{j+1}: $$Q_{j,j+1} = \frac{1}{2} * C_c * (s_j + s_{j+1}) + Q_i \quad (16)$$

If using subscripts p for predicted and o for original or initial, and account for simplification given in the equation (3), we can write the predicted mean mine inflow (Q_p) between the drawdown levels j and $j+1$ as:

$(Q_p)_{j,j+1}$ for drawdowns s_j and s_{j+1}: $$(Q_p)_{j,j+1} = (Q_o - Q_{io}) * \frac{1}{2}\frac{s_j + s_{j+1}}{s_o} + Q_{ip} \quad (17)$$

The last equation is better suited for cases where no exact data on the aquifer bottom wall level exist. Equations for the volumes can be then modified accordingly by substituting $(h_{j+1} - h_j)$ for $(s_j - s_{j+1})$. Regardless of the equation applied, the predicted time $(t_p)_{j,j+1}$ required for the groundwater to rebound within the mine from the level j to level $j+1$, when taking into account predicted total volume (V_{tp}) and predicted mine inflow (Q_p), is equal to:

$(t_p)_{j,j+1}$ related to levels h_j and h_{j+1}: $$(t_p)_{j,j+1} = \frac{(V_{tp})_{j,j+1}}{(Q_p)_{j,j+1}} \quad (18)$$

Finally, the overall predicted time, required by the groundwater to rebound from its initial active dewatering level h_o before the mine closure to a given level h_m is equal to:

$(t_p)_{o,m}$ related to levels h_o and h_m: $$(t_p)_{o,m} = \sum_{j=0}^{m} (t_p)_{j,j+1} \quad (19)$$

In first approximation groundwater rebound level within a mine was taken during our approach to be equal over the whole area of the mine and to be a function of its flooding time only. When looking into details, small pressure differences do exist between the different parts of mine structure, allowing the water to flow towards structures with lesser water inflow. In case of an individual mine this remark may seem fully meaningless, related to the importance of the involved groundwater level rebounds. Yet in case of connected mines or coal fields, these pressure differences can be important factors of mine induced modifications of regional aquifer flow and inter-aquifer flow. Though at first hardly perceptible, they may create serious problems during the latest stages or at the end of the groundwater rebound.

Rebound prediction uncertainties

Rebound prediction involved parameters are subject to measurement or determination errors. In depressed conditions normally preceding a mine closure, we will seldom get data on initial mine discharge Q_o having less than 5-10 % error and will be happy to know the initial infiltration or overburden inflow water rate Q_{io} with a precision of 10-20%. We may therefore easily expect to introduce a total mine inflow estimate error of the order of 10%. As far as the available void volumes are considered, the situation is much less clear. If we adopt the engineering tendency to look after the conservative estimates and dispose of good mine plans, we will hopefully make no more than 10 % error on the volume of the persistent mine openings, but may easily stay 20-30% below the true value.

It will be worse for the available void volume of the consolidated backfill. In trying to be conservative, we will hopefully make no more than 20-30% of overestimate error, but may well stay 100-200% below the real value. And still worse will be our estimate of the porosity of the caved in material. If taken conservatively, it may easily be overestimated by 50% and underestimated by at least 200%. Similar to this will be a conservative estimate of effective porosity of the involved aquifer. The worst will be for the estimate of the volume of cone of depression. By being very conservative, we may probably induce no overestimating error. This is fine. However, by doing so, we may well underestimate its volume by hundreds of percent.

From the above discussion it is obvious than a mine's groundwater rebound prognosis must be given for a range of probable values. Only by such an approach and careful subsequent groundwater rebound monitoring will the unpleasant surprises be avoided.

It is important to note that in the case of mines in important and well permeable aquifers, the initial infiltration inflow rate Q_{io} may well substantially change during the mine flooding process and may present a quite important portion of the total mine inflow. It was not an intended mine flooding case, but it is worth noting here as an extreme the Cadjebut Mine case of Western Australia (a personal communication of Andrew Bailey from BHP Engineering). This about 500 m deep Pb-Zn mine was situated in an arid area in a karst limestone aquifer of regional extension. Past dewatering created a cone of depression of regional dimensions. In years 1988/89, a 6 days rain with 344 mm of total precipitation completely refilled the aquifer and totally flooded the mine! By presenting this example, we do not pretend that something similar may happen in the humid climate. But periodic or annual infiltration inflow variability, exceeding 50% of the mine's mean discharge has been recorded in many a mine, working in humid conditions.

When fitting mine groundwater rebound prognoses to the short preliminary rebound tests, it must be noted that from the aspect of the involved aquifers, a groundwater rebound is a dynamic process. In first approximation, it may be assimilated to a groundwater rebound around a large volume well, first rebounding relatively slowly and then gaining momentum. Adequate solutions are given elsewhere 10 . Regional groundwater rebounds around mines, mine groups or mine fields situated within aquifers or low permeable rock will also be affected by this fact. For regional groundwater rebound prognoses, however, water budgets of the involved aquifers must be carefully elaborated. Mathematical modelling should be applied only when adequate data exist.

It is important to note that in cases of mines or interconnected mine groups and mine fields, located in low or poorly permeable rocks, the remaining mine openings may drain water from areas with higher water levels and convey it to areas with low water levels, acting for the surrounding rocks as a closed circulation convection system without much visible impact on its surroundings. Unless, however, these mines or mine fields have low level surface entrances, which may be transformed in low level water outlets. In such cases, these mines will act as rock massive's drainage and discharge groundwater to the surface.

GROUNDWATER PREDICTION - CASE STUDIES

The Durham Coalfield, UK.

The Durham Coalfield, located on the north east coast of England, was one of the major coalfields in the UK and produced a maximum tonnage of 56 million in 1915. From the 1960's there was a rapid decline in production and by 1987 the coalfield only produced 9 Million tonnes from a few pits located on the coast. These remaining pits pumped about 2200 litres/second of relatively unpolluted water that complied with the environmental limits set at the time. The large volumes of water were pumped from over 25 satellite pumping stations located up-dip of the 400+m deep pits (See Figure 1).

By 1993 all the pits had closed for economic reasons due to privatisation of the industry and, apart from the huge social problems, it was anticipated by some that the cessation of pumping would cause widespread flooding, gas migration and river pollution.

On closure of the coalfield in 1994 there were 10 pumping stations, the locations of wich are shown in Figure 1, pumping a total of 1100 litres/second into the local river system and the North Sea. The water was generally neutral with a total iron content of up to 8 ppm.

Environmental pressure groups, local government and environmental agencies (NRA 1994) were concerned about pollution of river water, especially the visual effect on the River Wear which flows beside Durham Cathedral (a world heritage site), pollution of potable water supplies and surface flooding and other geotechnical problems in low lying areas in the valley bottoms. Quite often their campaign was waged in the press and on national television and they gained considerable support for their ill-found idea that a widespread catastrophe was imminent.

However, the coal industry for many years had been predicting the outcome of mine closure and the first reports written in 1981 (NCB 1981), were, on hindsight, found to be accurate in that little flooding or pollution would occur if a selection of the pumps were kept running. Later reports (BCC 1992 and Norton 1994) also confirmed this and predicted an improvement in water quality once equilibrium status had been reached. It took until the present year for the environmentalists to accept the industry's prognostications. In the meantime considerable amounts of government money has been wasted in trying to refute their often lurid statements and to date no notable pollution has occurred.

Now, three years after closure only 5 pumps are working to maintain the water level about 50 m to 100 m below ground level at a cost of around £1 Million per annum and some water treatment is being undertaken with chemicals and wetlands to maintain pH between 6 and 8 and Fe below 1.5 ppm and the situation is under control.

This example perhaps serves to prove the fact that industry is better equipped to predict and to deal with its own problems and that the unwarranted fears of the environmentalists about mine closure are often unfounded. It is interesting to note that recently the European Commission has authorised the UK government to provide 891 Million to its coal industry until 2002 to cover social and environmental liabilities inherited since privatisation. Finance for groundwater rebound remediation will be included in this deal.

Wheal Jane Tin Mine

This mine is located in the far south west of the UK in Cornwall and closed in 1991 and was the last mine in an area of hydrogeologically interconnected tin mining extending over 35 square kilometres. The mine was dewatered to a depth of over 1000 m and once it was realised that mining was no longer economical because of the collapse of the world tin market price then mine closure was inevitable.

The pumps were withdrawn in March 1991 and it was therefore necessary to predict the rate of rise of the groundwater, where it would issue at surface and the potential for pollution of surface streams. The mine owners did not have any money for dealing with the potential problems and under current mining law in the UK it was proved (Norton 1991) that they were not responsible for the pollution resulting from a legally closed mine (Water Act 1989).

The finance therefore had to come from the government environmental agencies to fund treatment of the mine water. To date about £11 Million has been spent on chemical treatment and a pilot wetland facility.

From experience it was shown that prediction of the rate of rise of the water in the mine voids could be very accurate and in a relatively enclosed system such as that at Wheal Jane where considerable knowledge of the mine workings, how they interconnect with other mines in the area and the existence of a regional mine dewatering system of galleries, the water rise proved to be exponential. When the pumps were switched off it was therefore predicted that the water would reach surface about 9 months and in actual fact it issued forth on 21.11.97 within a few weeks of the date predicted (Norton 1991).

However, prediction of the pollution effect was underestimated and in January 1992 an old underground water barrier burst in a connected mine and a catastrophic outflow of grossly polluted water issued into the receiving River Carnon which attracted worldwide media attention. The barrier had been constructed to the best technology available in 1937 but due to the acidity of the rising water had been unable to withstand even a minor head of water of about 7 m.

About 50.000 cubic metres of mine water burst forth into the river and was grossly polluted with a pH of 2 and containing very toxic amounts of cadmium, copper, lead, arsenic, mercury, zinc, iron and manganese. In fact the pollution event was so great that an orange stain could be seen in the sea for several kilometres off shore.

It was noted that during the period of water rise that there was a considerable variation in the chemistry of the mine water. The pH, for example, varied between 2 and 6.5 and there was a corresponding rise in toxic metal content with increased acidity. Some of the changes were very rapid and on a daily or even hourly scale. The reason for this is not fully understood but convection in the rising waters with rapid dissolution of toxic metal sulphates lining the mine cavities is thought ta be the reason.

There is no doubt that the use of continuous monitoring of mine water chemistry in similar situations is to very much recommended in all future studies. The placing of monitoring instruments in the mine at as many various locations and depths as possible before groundwater rise is advisable so as to obtain the best picture of situation. The equipment should be robust to survive the aggressive environment, be capable of withstanding high acidities and be able to measure important indicator metals and salts such as iron, calcium, copper, sulphates and chlorides etc. as well as pH.

Polluted mine water continues to issue from Wheal Jane although, as predicted, the amount of toxic metals is gradually reducing but it is likely that a considerable amount of money will still be needed for the foreseeable future to treat a volume up to 300 litres/second. Treatment methods much less expensive than the chemical methods presently employed will need to be found to reduce the annual treatment budget.

Loke Mine of the Zagorje Brown Coal Mine Company

Loke mine is situated in a complex, imbricated structure of the southern flank of the Zagorje syncline, between the eastern lying Zagorje and western lying Loke faults. The mine shaft's entrance is situated at 275 metres above sea level. Triassic dolomite is not outcropping in this area, but is covered by impervious Tertiary strata. In some individual imbricate units it can reach up to a level of +130, while outside these units it does not exceed a level -100. In a block, limited farther to the east by Ržiše fault is the dolomite basement of tertiary strata lowered to the east of Zagorje fault for 500 metres. To the east of the eastern part of Loke mine starts the dolomite basement to rise sharply between the Zagorje and Loke faults towards the Toplice area. It outcrops there in an area of 0.02 km^2. The dolomite basement is lifted in the southern flank of the Loke fault, but does not outcrop there and is gradually dipping towards the south, contacting the dolomite structure of Vrh and Čolnišče no closer than 400-500 metres southwards from this fault. A facies border lying just 200-300 metres to the north of the Zagorje syncline's axis, is limiting the pervious Triassic dolomite against the impervious Pseudo-zila strata and preventing its hydraulic connection to the dolomite masses of its northern flank.

A recharge of the Loke mine area's dolomite blocks could be expected only from the east, west or south, with a key role in its control being played by the zones of mylonitized dolomite along the Ržiše, Zagorje and Loke normal faults and the imbricated structure thrust faults. Experiences show that such zones prevent groundwater flow across fault planes in the Triassic dolomites. Dewatering inflow and post dewatering rebound data show that groundwater enters the dolomite basement of the Loke mine mainly from the dolomite block, situated between the Zagorje and Loke faults to the southeast of the mine, dewatering also this dolomite block. The thrust faulting zones within the dolomite are therefore not totally impervious.

In a mine closure's groundwater rebound prognosis (6,7), the mine inflow estimates were given for the Loke mine from the past dewatering records of this and nearby Kotredež mine with the application of previously given equations (3), (4) and (5):

Level (m)	-50	-38	+20	+90	+150	+210	+275
Mine inflow (m^3/sec)	2.7-3.0	2.6-2.9	2.2-2.5	1.7-1.9	1.3-1.4	0.8-1.0	0.4-0.5

A first groundwater rebound prognosis was made in June 1990 (6) to predict the mine's water level rebound time from level -50 to its level +20 based on two rebound level data from the shaft 52 and one measurement record from shaft IV-V only. Its purpose was to predict the evacuation period for the level +20, after the stop of the pumps at the level -50. The mine void volumes, available for flooding, were calculated from past mine operational records, with consolidated backfill porosity being 10-15%, consolidated caved in weak rock type claystone and siltstone porosity 1-5% and the dolomite rock effective porosity 1-2%. The Loke fault was considered impervious and no dewatered rock supposed to exist south of this fault. With equations (9) through (14) and (16), the predicted conservative rebound time was between 97 and 152 days (or 200 days; with water level record from shaft IV-V). The actual rebound time was about 320 days.

In March 1991, a further groundwater rebound prognosis was made based on past rebound data, admitting for Loke fault to be partly pervious and dolomite block in its southern flank partly dewatered. Several scenarios were calculated from different possible backfill, caved in rock and dolomite porosities. Minimum and maximum void volume and rebound time estimates were:

Flooding levels (m)	V_{min} (m^3)	Time (days)	V_{max} (m^3)	Time (days)
-50 - +20		320		320
+20 - +90	881.350	589 - 634	1.118.700	673 - 718
+90 - +150	482.350	801 - 857	532.700	897 - 965
+150 - +210	379.350	1020 - 1108	391.700	1124 - 1224
+210 - +270	275.350	1274 - 1427	322.700	1423 - 1597

The above two prognoses are given in the Figure 3 as rebound curves 1 and 2, giving minimum and maximum calculated rebound times respectively. In parallel, a rebound prognosis based on a polynomial derived from the mine's groundwater rebound data, was tempted. Though being purely mathematical extrapolation, it is conceptually based on the presumption that the mine surrounding dewatered dolomite blocks act as a big diameter well in more or less continuous aquifer. This rebound prognosis is presented on the Figure 3 as curve 3.

With respect to the stability of shallow lying Tertiary strata, it was important to make also a long term groundwater rebound prognosis. Following the presumption related to the curve 3, it was further admitted, that after these dolomite blocks are flooded with water, the whole dolomite aquifer will rebound according to its transmisivity. With long term rebound prognosis, the potential groundwater outlet levels being either within the Toplice area dolomite outcrop or lower within the Medija river valley. These long term prognoses are given as curves 4 and 5.

Rectangles, given on the Figure 3 illustrate the actual groundwater rebound in the mine. Ground-water rebound closely follows the polynomial extrapolation. It is still uncertain, which of the two long term rebound prognoses is going to be correct. We believe that this example proves that in a complicated structural and hydrogeologic setting, as conservative as possible rebound prognosis must be followed by continuous rebound monitoring and steadily amended if necessary.

Mežica Pb-Zn Mine

Mežica mine was mining ore bodies within the Triassic carbonate rocks, mostly dolomites, forming a regionally important karst aquifer. In 1935, the mine started production below the local hydrological base level +500, represented by the river Meža. Since then, dewatering of the mine was necessary. On the Figure 4, a record of the past mean annual mine inflow versus the active dewatering level shows that the maximum mean annual inflow at a level generally followed a certain dewatering roadway development at that level, suggesting a compartmented aquifer. For the dewatering level +300, active before the mine=s closure, it has been demonstrated that the inflow can be statistically totally explained by the past rainfall. The cone of depression was fully developed and stable. From aquifer water budget calculations, his area was estimated to 83 km^2. Only the volume of drained rock voids between levels 300 and 353 was amounted to $5.2*10^7$ m^3. Mean daily inflows to level +300 were between 56 and 28 m^3/min and are season related.

For a prognosis of groundwater rebound from level +300 to +417 after the mine closure were adopted the mean daily inflow rate of 33-38 m^3/min and a depth inflow rate decrement of 0.2 m^3/min/m. Rebound times from data on the existing mine openings were calculated, but it was felt that probable rebound time will be close to that based on the dewatered aquifer voids volume.

Mine level	+353	+372	+392	+417
Mine openings volume only	9.7 days	16 days	25.8 days	33.6 days
Aquifer void volume added	913 days	1006 days	1117 days	1245 days

The flooding started in December 1994. Last recorded mine water inflow rate was at the lower end of the adopted range and the observed groundwater level rebound times were as follows:

Mine level	+311	+320	+350	+368	+390	+418
Time lap	5 days	10 days	37 days	58 days	86 days	119 days

Observed discrepancies in groundwater rebound rates when accounting for the aquifer void volume are tremendous. What went wrong with the prognosis? Even when only the rock volume directly above the mine area were taken into account and an effective porosity of n_e =1%, seemingly adequate in the Loke mine case, the rebound time for the level +417 would still be 240 days. Here, the effective porosity of the aquifer during the rebound was obviously below n_e = 0.5%. This is low, but not unexpected for a karst aquifer. It must be noted that the polynomial based prognosis was correct again, but not before close to 30 days of actual flooding record was available. It would be therefore useless for a prognosis before the mine flooding started. We must conclude, that in that case, the rebound prognosis was simply not enough conservative.

CONCLUSION

When mining deep under the local groundwater level required great local water level lowering, groundwater rebound is the most obvious and dramatic of all the mine closure environmental effects. It is of vital technical and environmental interest to make the best possible groundwater rebound prognoses. Any substantial discrepancies may lead to wrong decisions, to potential damage and to related financial losses and legal claims.

Conceptually, the groundwater rebound is a simple phenomenon, dependant on just two parameters: the void volume to be filled up with water within the mine and the dewatered parts of the aquifer and the water inflow to fill the dewatered void volumes. Unfortunately, a good estimate of the total available void volume is far from being easy. The uncertainty of the estimate of the total void volume available for flooding will be generally greatest for the mines within the aquifer and smallest for the mines forming primary water bearing structure within a poorly permeable strata. Compared to this, a reliable estimate of groundwater inflow is more easily obtained, but still bound to inevitable error.

After the study of many cases it is the authors' contention that groundwater rebound in abandoned mines is a very difficult subject for computer modelling and many false claims are made from such programs without the benefit of a full and reliable basis of insitu monitoring data. Prediction of the effects of groundwater rebound on closure of mines is a difficult science and must be based on rigorously employed monitoring and experience.

REFERENCES

1. Rogoz M. 1978. Water Capacity of the Abandoned Workings in Underground Coal Mines. Proc.Int. Conf. " Water in Mining and Underground Works", SIAMOS, Granada, Spain.
2. Rogoz M. 1994. Computer Simulation of the Process of Flooding up a Group of Mines. In: Reddish D. J. (Ed.). Proceedings. 5th International Mine Water Congress, 1, 369-377, ISBN 0 9524318 0 7, University of Nottingham & IMWA, Nottingham.
3. Sherwood J.M. & Younger P.L. 1994. Modelling Groundwater Rebound after Coalfield Closure: An Example from County Durham, UK. In: Reddish D. J. (Ed.). Proceedings. 5th International Mine Water Congress, 2, 769-777, ISBN 0 9524318 0 7, University of Nottingham & IMWA, Nottingham.
4. Norton P. 1995. The Impact of Mine Closure on Ground Water and the Environment: A UK Lesson for all Countries. In: Hotchkiss W.R., Downey J.S., Gutentag E.D. & Moore J.E. (Eds.). Water Resources at Risk. IMWA-85-IMWA-91, LCCCN 95-079662, AIH, Minneapolis.
5. Meyer J. & Schuppan W. 1995. Information zur Flutung der westerzgebirgischen Urangrube Pöhla der WISMUT GmbH. In: Merkel B., Hurst S., Löhnert E.P. & Struckmeier W. (Eds.).Uranium-Mining and Hydrogeology. GeoCongress 1, 369-375, ISBN 3-87361-256-9, Verlag Sven von Loga, Köln.
6. Veselič M. & Božović M. 1990. Hidrogeološka ocena hitrosti potapljanja jame Loke med 5. In 4. obzorjem. (Hydrogeologic estimate of the rate of flooding of the Loke coal pit between the 5th and the 4th mine levels). GZL-IGGG Report Nr. 184-1/90 (unedited), 10p., GZL-IGGG. Ljubljana.
7. Veselič M. & Ribičič M. 1991. Ocena vpliva potapljanja jame Loke na stabilnost površine terena na širšem obmo ju jame. (Estimate of the influence of flooding of the Loke coal mine on the surface stability of the coal mines broader suroundings). GZL-IGGG Report Nr. 139-1/91 (unedited), 16p., GZL-IGGG, Ljubljana.
8. Veselič M., Prestor J. & Junež P. 1989. Hidrogeološka problematika rudnika Mežica (Hidrogeologic problems of Mežica mine). GZL-IGGG Report Nr. 148-1/89 (unedited), 53p.+13an., GZL-IGGG. Ljubljana.
9. Prestor J. 1994. Dinamika zapolnjevanja rudnika Mežica po prekinitvi črpanja. GZL-IGGG Report Nr. nnn-n/nn (unedited), np., GZL-IGGG, Ljubljana.
10. Veselič M. 1978. Exemple d'étude d'un aquifère alluvial semicaptif - Implantation des puits de production - Interprétation des pompages d'essai -Optimisation d'un groupe de puits. 96p.+2an.+52ap. PhD Thesis. Université de Bordeaux I.

11. National Coal Board (1981): Report on pumping in the Northumberland and Durham Coalfield, Part 2 - The Future. 22pp, Newcastle UK.
12. National Rivers Authority (1993): Study of the regional hydrogeology of the Durham Coalfield and potential impact of ceasing mine dewatering, UK.
13. Peter J Norton Associates (1994): The potential for river pollution from abandoned mine in the Durham Coalfield. 68pp, Richmond, UK.
14. British Coal Corporation (1992): Report on mine water pumping and water problems in the Northumberland and Durham Coalfield Area. 44pp, Durham, UK.
15. Peter J Norton Associates (1991): Report on Groundwater rebound at Wheal Jane for Carnon Holdings Ltd. 42pp, Richmond, UK.

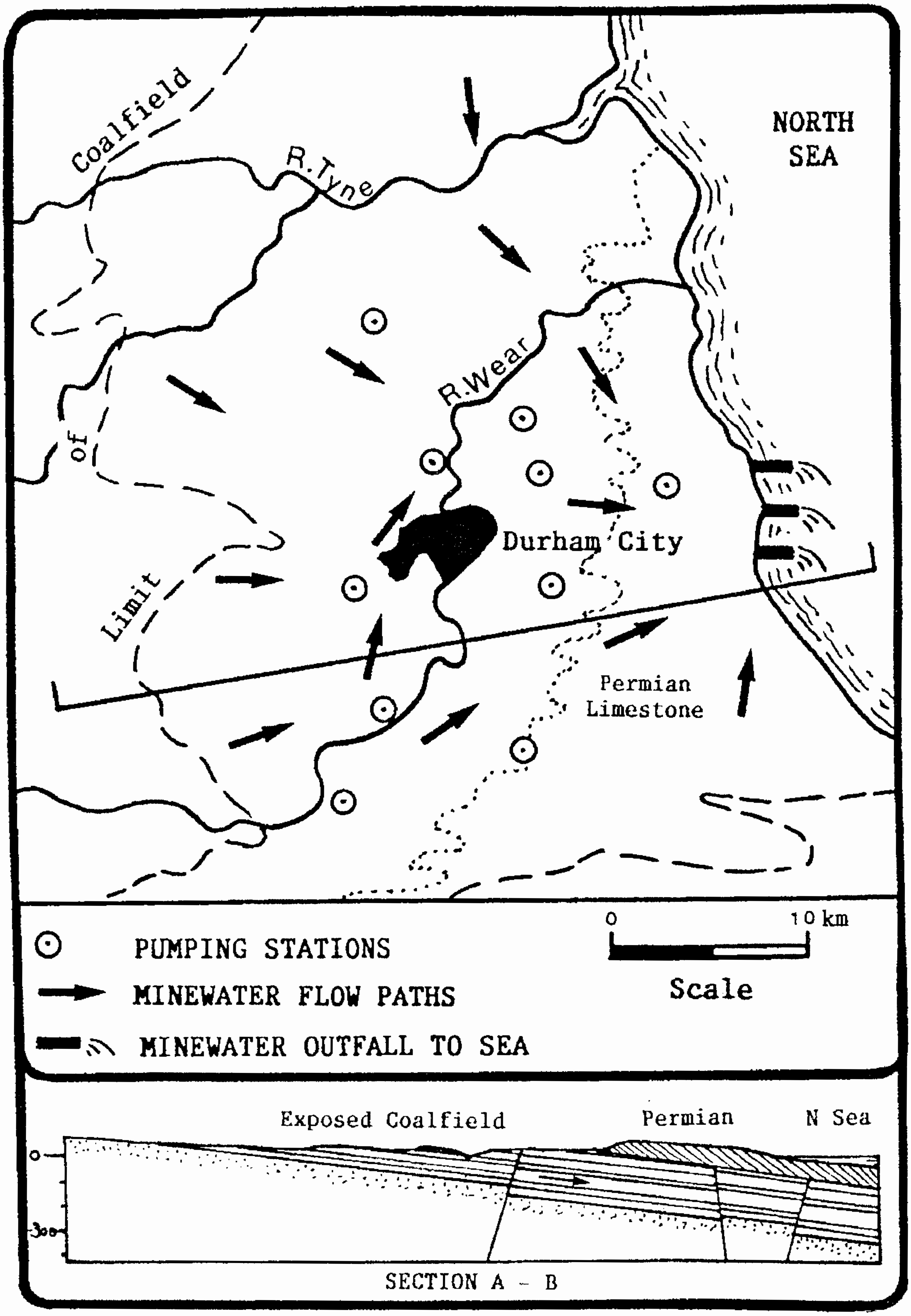

Fig. 1 : THE DURHAM COALFIELD

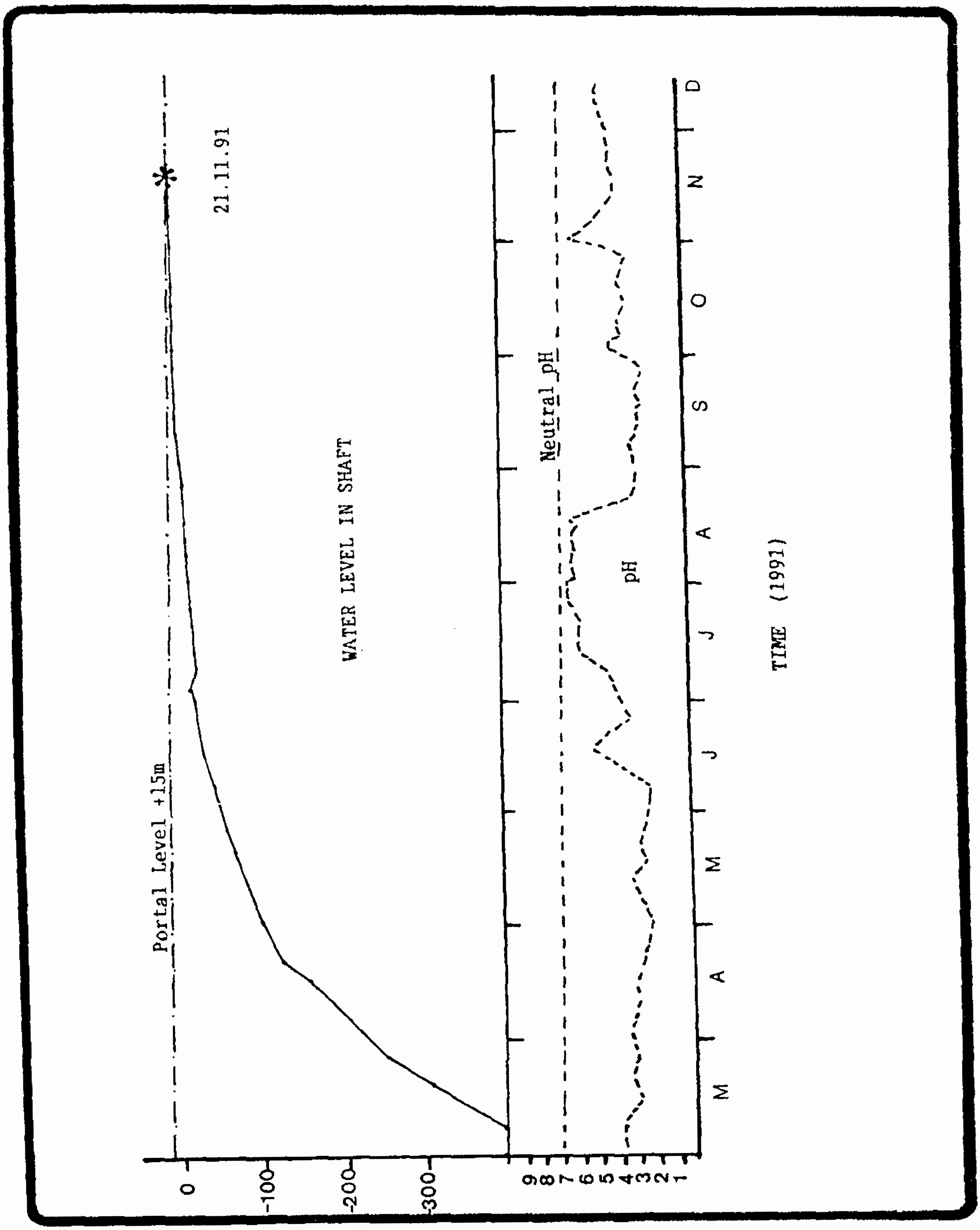

Fig. 2 : WHEAL JANE TIN MINE; WATER RISE IN SHAFT AND WATER QUALITY (AFTER NORTON)

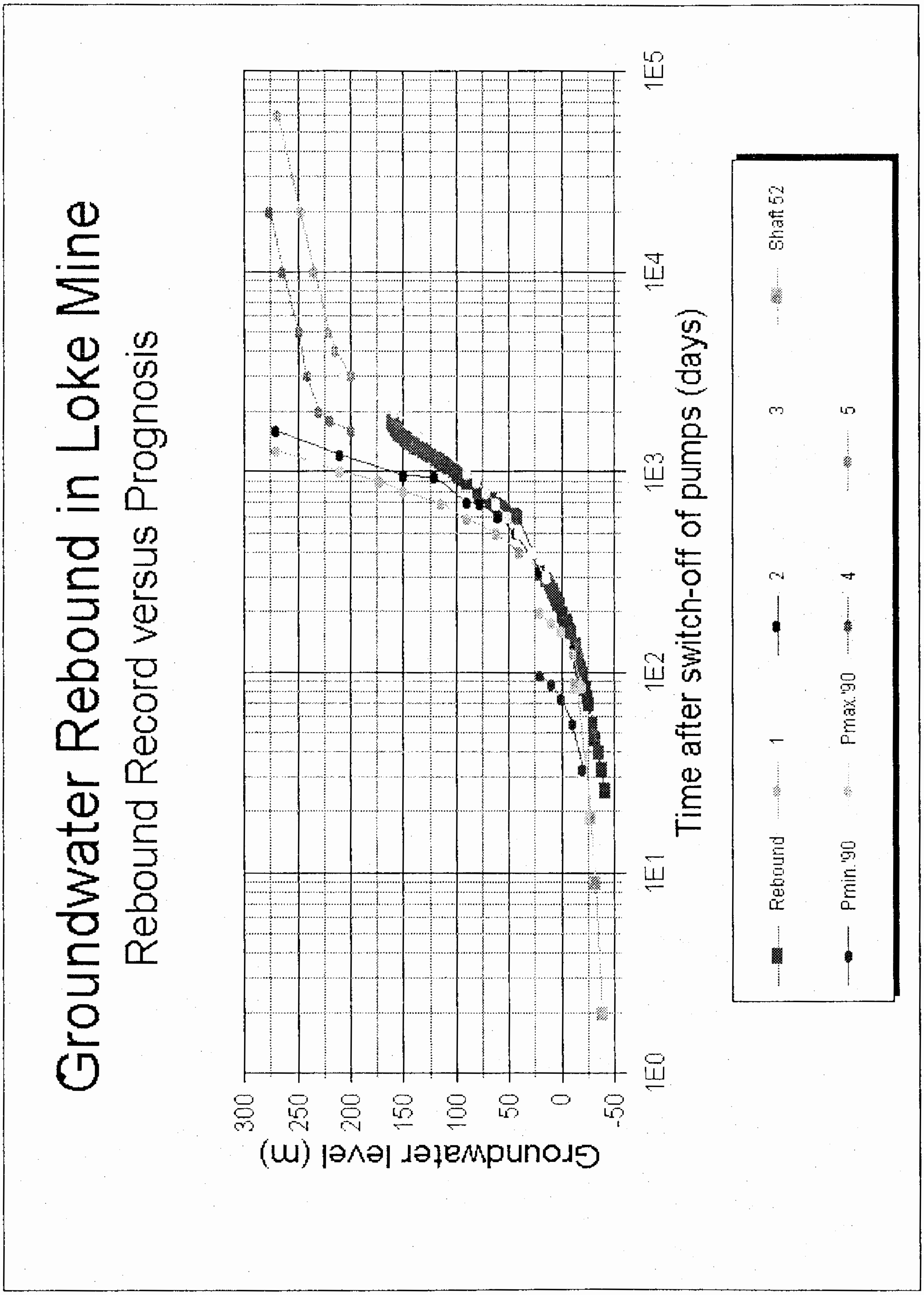

Fig 3 : Groundwater Rebound in Loke Mine

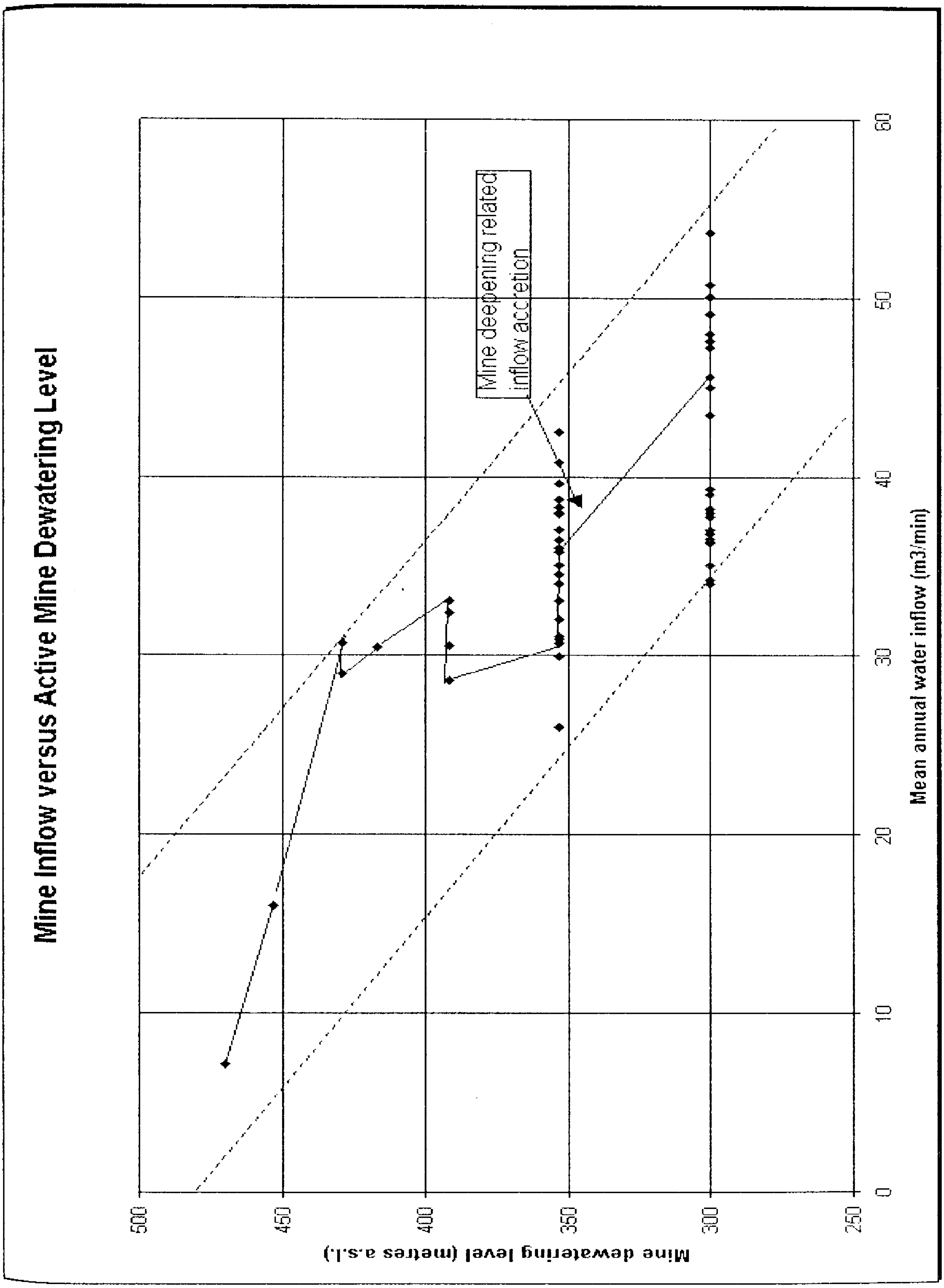

Fig. 4: Mine Inflow versus Active Mine Dewatering Level