Modelling Groundwater Rebound after Coalfield Closure: An Example from County Durham, UK.

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ABSTRACT

Paradoxically, efforts to predict the rate and spatial variation in groundwater rebound after coalfield closure are hindered by both the lack and superabundance of various kinds of data. There is generally a 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 these hydraulic parameters and the hydrogeologically "non-standard" nature of underground workings. On the other hand, mine abandonment plans are often so complicated that detailed synthesis of such records for purposes of regional hydrogeological analysis is a truly Herculean task. Furthermore it is by no means clear whether standard Darcian approaches to aquifer modelling are really applicable to mined strata. Confronted with these problems, a lumped parameter modelling approach has been developed which relies on physical characteristics of the system, without demanding complete specification of permeabilities. Deterministic modelling of groundwater rebound in the large (5000km^2; 14 seams) abandoned coalfield of County Durham using this approach yielded results comparable to those obtained using a standard darcian model. Both studies indicated the critical dependence of predictions on the value of storage coefficient (void ratio) assigned to the old workings and intervening start. Unlike the standard darcian model, the lumped parameter code is sufficiently economic in terms of cpu time that it lends itself readily to Monte Carlo simulations. The resulting probabilistic predictions are more "honest" than straightforward deterministic results.

INTRODUCTION

The recent large-scale colliery closures in Britain will have a fundamental effect on the hydrogeology of the coal mining regions. In many cases the collieries that have been closed are the sole survivors of once extensively worked coalfields. Mine dewatering requirements have resulted in the maintenance of lowered water levels over large areas of coalfield. Therefore closure of these mines will result in groundwater rebound not only in the mines themselves, but in interconnected old workings over large areas [1]. In the case of the Durham Coalfield, a great area of the coalfield, including many long abandoned mines, has had artificially lowered water levels for decades, and in some areas hundreds of years. When a colliery is closed there is no longer an operational need for mine dewatering and it therefore seems reasonable that it should cease. However cessation of mine dewatering leads to groundwater rebound and the generation of acid mine drainage.

THE DURHAM COALFIELD

Location and History.

The Durham Coalfield is situated in the North East of England. The main hydrologically interconnected area of the coalfield, where the groundwater level has not yet been allowed to rebound is bounded to the north by the River Tyne, to the south by the Butterknowle Fault and offshore workings extend 8km off the east coast. It is made up of Carboniferous Westphalian Coal Measures of stages A, B and C which total approximately 900m. To the west of a line through Ferryhill (Bishop Auckland) and Boldon (near South Shields) the coalfield is exposed. To the east the Coal Measures are overlain by the Permian Basal Sands and Magnesian Limestone aquifers.

Prior to the recent closures, seams in the offshore area were still worked from Easington and Vane Tempest Collieries (Figure 1). These collieries were dewatered; however pumping at nine inland abandoned pits was also required to prevent flow towards the coast. At the time of writing (June 1994) pumping at the coast has ceased but continues at the nine inland sites.

Deep mining of the Durham Coalfield began in earnest with the invention of the Newcomen pumping engine in the early eighteenth century. Mining began with shallow workings in the exposed coalfield. As technology improved workings became deeper and extended into the concealed coalfield. This led to a large scale drawdown of the water table. This lowered water level has been maintained in much of the coalfield until the present day. There are no longer any working mines in the Durham Coalfield however, the result of a cessation of pumping would be groundwater rebound throughout the coalfield and the possible generation of acid mine drainage on a large scale.

Potential Impacts of Groundwater Rebound.

The water from the current pumping regime is of a reasonable quality and is used to augment flows in the Rivers Wear and Team [1,2]. In particular, the Kibblesworth discharge is used to dilute sewage effluent in the River Team (which is a tributary of the River Tyne). Loss of this source of water will mean less effluent dilution in the short term.

When poor quality mine water eventually discharges at the surface it will pollute the Rivers Wear and Team. The orange ochre coating of beds and banks is an obvious aesthetic problem reducing amenity value. The ochre which forms at the surface discharge point coats vegetation smothering it and killing benthic invertebrates.

North East Water's Lumley intake on the River Wear amounts to 20% of Sunderland's water supply [1]. Should the water quality get so bad that this water source has to be replaced the cost will be £24 million [3]. Groundwater pollution could contaminate the Basal Permian Sands and Magnesian Limestone which represent a large part of the public water supply for the southern part of the Sunderland District and the whole of Hartlepool. There are also many private boreholes in these aquifers.

Geotechnical problems might include leaching from landfills [4] and sulphate in polluted groundwater attacking cement foundations and infrastructure. As the rising water intersects old bord and pillar workings there could be an increased risk of subsidence [1]. There is also likely to be a short term increase in methane emissions.

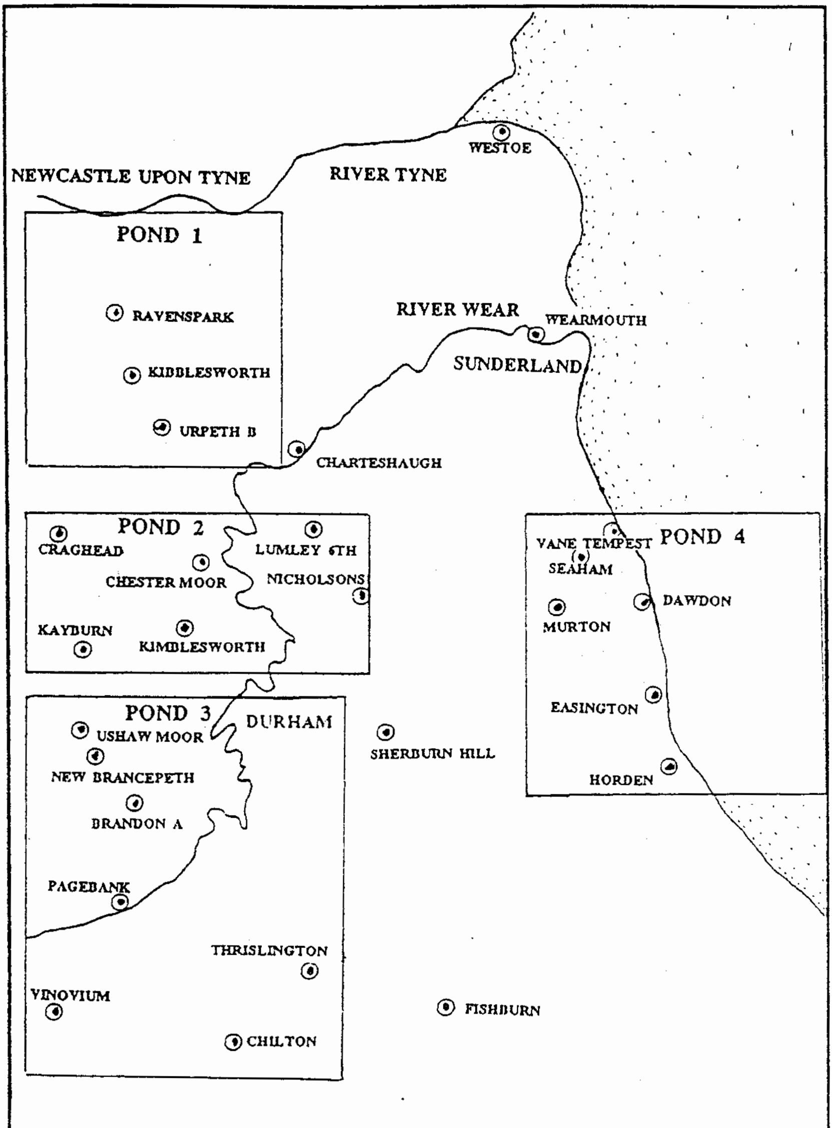


***Figure 1**: Locations of "Ponds" in abandoned deep coal workings of the Durham coalfield.*

MODELLING GROUNDWATER REBOUND

Modelling Approaches and Problems.

The NRA commissioned consultants to model the hydrogeology of the coalfield and the implications of discontinuing mine dewatering [5]. Standard groundwater modelling software was used to predict the rate at which the groundwater would rebound and thus the likely timing of discharges. However there are problems applying Darcian principles to extensively mined strata, because Darcy's law assumes simple porous media and laminar flow. Abandoned coalfields consist of interconnected workings, collapsed areas and areas of unworked coal which act as barriers. This environment can only be modelled as a simple porous media on a very large scale. Flow through open workings and roadways is more likely to be akin to turbulent stream flow rather than normal laminar groundwater flow.

Other problems which beset modelling in this system are:

(i) The scarcity of hydrogeological data. Even though much information on flows and quality of underground waters are collected during mining, operational needs at that time are markedly different from needs which arise during modelling of groundwater rebound. Furthermore, the rebound modeller wishes to know the water transmission and storage properties of hitherto dewatered mined strata, which by definition can never have been test-pumped. Hence available data are usually unsuited to modelling purposes.

(ii) Data describing geometry and nature of mined voids are seldom available in a suitable format. It would be an advantage not only to be able to divide between worked areas and barriers but also between areas mined using different techniques. While there are numerous mine plans available, the most crucial mined voids are those at shallowest depth, which are often the oldest also, and are therefore often absent from plans. Furthermore early mining plans frequently lack scale or orientation and are liable to be inaccurate because robbing of pillars and barriers was frequently unrecorded (for it was often undertaken illegally). Even where good plans are available, the degree of detail is often overwhelming and useable simplified syntheses are difficult to compile.

With problems such as these, detailed deterministic modelling would be a gargantuan task with an uncertain outcome. For these reasons a lumped parameter approach was taken. The only key assumption is that the water flow in the abandoned workings occurs rapidly. Following ideas and terminology which enjoy currency amongst British Coal engineers [6,7], the system is conceptualised as a system of four partially interconnected "ponds" to which the principle of mass conservation can be jointly and severally applied. The geometries of these ponds, in particular the positions of low permeability intact coal barriers separating the ponds, were deduced by analysis of water levels in areas affected by the dewatering pumps (when the coastal area was still being mined). Figure 1 shows approximate location of the idealised ponds used in the model. The area to the west and south of the ponds has already been allowed to rebound.

The approach has the advantage of modest data requirements. For each pond details of the areal extent, barrier height, the number of pathways over the barrier, water levels, height at which baseflow occurs and the pumping rate are required. One estimate of the hydrogeological and hydrological parameters for each pond is required. These parameters are: storativity, hydraulic conductivity, notional transmissivity and hydraulic gradient, percentage excess rainfall forming surface runoff and seepage rate from the Magnesian Limestone. Most of the hydrogeological data have been estimated from previous work in the area [5,6,7,8]. In particular the value of storativity (0.058) was based on work by Minett and others [7]. The estimate of seepage from the Magnesian Limestone (40 Ml/day) was calculated using a simple water balance.

Ponds 1, 2 and 3 (Figure 1) represent the inland region where different areas are pumped to different levels. Pond 4 represents the area of the most recent mine closures around Vane Tempest - Easington. (Westoe and Wearmouth are thought not to be hydraulically linked to the remainder of the coalfield and so are not included in the model). Each pond was assumed to settle to a level water table shortly after cessation of pumping. Subsequently the level of water in each pond rises as a function of recharge rate, flow between the ponds and seepage from the Magnesian Limestone. In this manner it is possible to calculate the time it would take for old workings in the ponds to fill with water, overspilling from pond to pond until water levels back up sufficiently that discharge commences at the surface. As the groundwater level rises to a high level the whole coalfield begins to function more as a single hydrological unit.

Using monthly time-steps, the model calculates the mass balance (between recharge, pumping, seepage and overspill rate) and calculates any incremental change in storage (in essence water level) within each pond. During early stages of the rebound, when overflow from pond to pond is probably restricted to relatively few roadways (N in total) and similar features, then overflow rate (Q_o) is calculated by a simple expression in which a notional distance travelled in a month by water flowing towards an overflow point is written as the radius of influence of that point. Velocities are calculated from generalised data from the literature describing hydraulic conductivities of worked coal measures. When the radii of influence of adjacent overflow points substantially overlap, overspill is calculated by an expression more akin to that describing flow over a broad-crested weir. At the end of each time-step the latest level of water in each pond is used to calculate minewater discharge to streams and other surface outflow points in the catchments of the Rivers Wear and Team.

Key Predictions.

Initial simulations were undertaken on the assumption that British Coal would follow their original intention and abandon all pumping stations at same time. Deterministic modelling with the lumped parameter code for this scenario predicts that Pond 3 (the most southerly) would rebound to the surface in 180 months (15 years). The central area around Chester-le-Street (Pond 2) would reach the surface next, about 30 years after the pumps were turned off. The northern area (Pond 1) which would pollute the Team valley rebounds to the surface last, within 40 years. The coastal area does not reach a level where it will cause surface discharges within the total simulation time of 58 years (see Figure 1).

As noted previously, British Coal's plans were modified after public debate on the issue and discussions with NRA, and at present (June 1994) pumping in the coastal pond has now stopped leaving only the nine inland shafts pumping. This means that Pond 4 is rebounding alone (See Figure 2).

Limitations of the Deterministic Model.

Clearly any deterministic model is limited by the quality of the data and concepts upon which it is based; uncertainties in either (which in this case are large) can only really be addressed by adopting a probabilistic approach to modelling, as discussed below.

FIGURE 2. PREDICTED WATER LEVELS IF ALL PUMPS ARE SWITCHED OFF SIMULTANEOUSLY

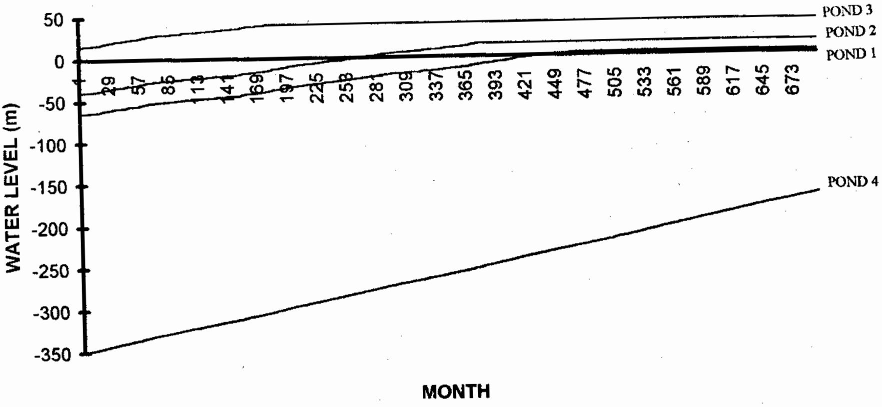


FIGURE 3. PREDICTED WATER LEVELS UNDER PRESENT PUMPING REGIME

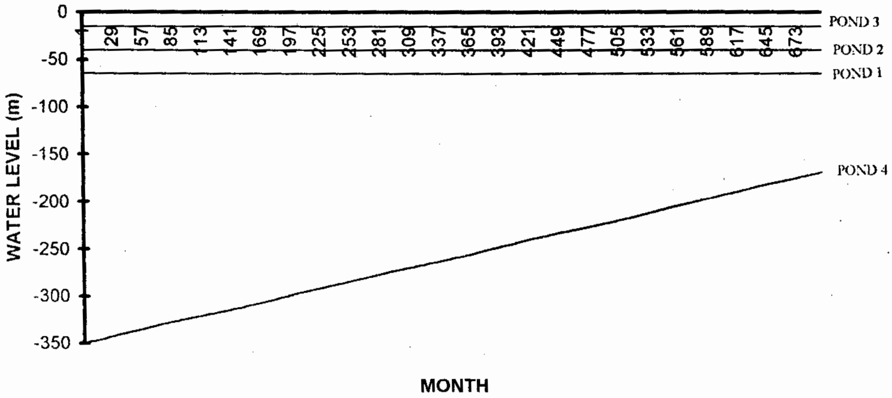
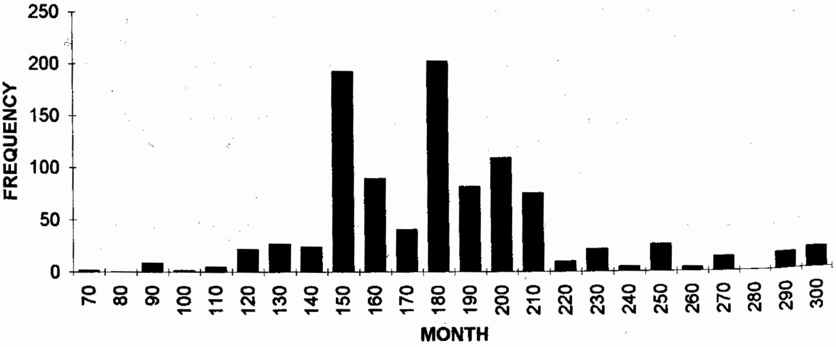


FIGURE 4. RESULTS OF MONTE CARLO SIMULATION OF THE TIME TAKEN BY THE GROUNDWATER LEVEL IN POND 3 TO REBOUND TO THE SURFACE



All models of groundwater rebound are sensitive to the storage parameter which is a measure of the percentage of void areas within the worked measures. Estimating this is very difficult and is perhaps the greatest source of error. There is also doubt about the accuracy of other data such as the inflow from the limestone.

The flat hydraulic gradient assumed over the ponds means that the graphs of the rebound levels are very straight. In actuality these are more likely to be curved as voids initially fill due to rapid flows under high gradient near the edges of the dewatered zone. This means that the initial predictions will be inaccurate. However, total term predictions converge with other possible solutions, for recharge and void volume are the ultimate controls in the system. But the overall prediction remains unchanged with a massive saving in computation.

It is impossible to predict exact locations at which water will emerge, even with standard groundwater modelling software, but the most likely sites are old shafts and drainage adits, fractures and long abandoned wells [9].

Monte Carlo Simulation.

Monte Carlo Simulation is a probabilistic approach to modelling in which the input and output of a model are defined in terms of probability distributions. This approach has the advantage of allowing for elements of uncertainty in the input data. To illustrate the potential of this approach, the model was run 1000 times with the values describing storage, pond geometry, water velocity, percentage direct run off and amount of seepage from the limestone all randomly sampled from populations defined by "mean" values (set equal to the values found acceptable in the deterministic runs) with standard deviations set at 10% of the mean for all parameters as a first approximation. The parameter values for each pond varied independently.

The model output takes the form of frequency distributions for desired variables. For instance, Figure 4 gives the distribution of time taken for complete rebound in pond 3. The corresponding mean rates of uncontrolled minewater discharge after complete rebound fall in the range 60 to 75 Ml/d.

Future work will necessitate definition of more appropriate probability distributions for each variable, then combining results of updated simulations with hydrochemical concepts to define probabilistic inputs to simulations of the impacts of future uncontrolled minewater discharges on the river systems.

CONCLUSIONS

Modelling groundwater rebound in coalfields is blighted by a lack of appropriate data. The lumped parameter model described here is a simple robust approach that overcomes some of the problems encountered in using off-the-shelf groundwater models.

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