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A simple, low-cost approach to predicting the hydrogeological consequences of coalfield closure as a basis for best practice in long-term management.

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Abstract

The closure of individual coal mines usually entails a cessation of mine dewatering, which can give rise to significant changes in the local and regional hydrogeological regime. Where the last colliery in an entire coalfield closes, these changes can be very large-scale and potentially damaging, with potential for pollution of major rivers and aquifers. While a number of modelling approaches have been developed in recent decades to predict these changes and facilitate their proactive (and prophylactic) management, when the last mine in a given coalfield is closing the mine owners typically have neither the time nor money to commission extended and sophisticated numerical modelling studies. In such circumstances, a simplified, lower-cost approach is required to provide regulators with predictions of rates of water level rise, future equilibrium water levels and the rates and quality of any future outflows of mine water to rivers and / or aquifers. These predictions can also be useful in guiding the decisions of future site owners over alternative uses of colliery infrastructure after the cessation of coal production. An approach to such predictions has been developed which is based on summary information on the extent of workings, dewatering pumping rates, locations and collar elevations of unfilled shafts and adits attached to the deep workings, as well as surface topography and the geometry of any overlying aquifers. Uncertainties over hydraulic gradient after the completion of water level recovery are handled by analogy to a range of post-recovery gradients from similar large coalfields. A brief example of the application of the approach to a real coalfield is presented. This approach could be used either on its own or as a prelude to more detailed modelling and monitoring during the years following mine closure. The insights into system behaviour gained from such exercises could well be valuable in future re-use of flooded voids as resources for heat recovery or disposal as part of low-carbon heating systems.

Highlights

- Prediction of the hydrogeological behaviour of abandoned coalfields
- Quantifies the duration of flooding till rest water levels are reached
- Identifies the mined features most likely to give rise to polluted outflows
- Allows prioritisation of post-closure treatment of major shafts

Keywords: coal, closure, groundwater, hydrogeology, mine, prediction

1. Introduction

1.1. Why predict post-closure hydrogeology of coalfields?

Deep mining of coal almost always extends below the water table and as such entails disruption of natural hydrogeological conditions. For the miner, the main consequence of this is a requirement for sustained mine dewatering throughout the life of the mine. In dewatering operations, pumps are operated at strategic points within and around the mine complex to remove as much water is as necessary to prevent flooding of active parts of the workings (Younger *et al.* 2002). The pumped water is typically discharged to surface water bodies. There are notable cases where disposal of such effluents has caused gross pollution of rivers (e.g. Hamill 1980); however, where pumped colliery effluents are treated to remove suspended solids, iron and any other major pollutants, the dewatering operations of active coal mines often have little noticeable effect on the surface water environment. After colliery closure, however, cessation of dewatering leads to a gradual flooding of the mine workings, which entails rapid dissolution of the efflorescent salts that have typically developed in drained, ventilated areas by oxidation of pyrite. This wholesale dissolution event often amounts to a 'geochemical trauma', in which the quality of water in the workings deteriorates considerably compared to the quality of water pumped before closure (Younger 1993a, 1998). When the flood level in the workings finally reaches a point at which overspill to the surface environment can occur, dramatic pollution of surface watercourses can occur, with devastating consequences for water resources and the ecological status of the receiving waters (Younger *et al.* 2002). Most documented cases of water pollution from abandoned coal mines relate to rivers; only one thoroughly-documented case of pollution of a major freshwater aquifer is known (Neymeyer *et al.* 2007), and the rare cases of marine water pollution by coal mine outflows are actually ambiguous, with the addition of iron to the sea (in which it is typically a limiting nutrient) being reported to enhance local marine life in some cases (Younger 2008).

Concern over colliery closure therefore tends to focus on assessing the risk of pollution of rivers and / or overlying aquifers when mine flooding culminates in the uncontrolled outflow of polluted waters into the freshwater environment (e.g. Henton 1979, 1981; Younger 1993a). Once established, mine water outflows tend to be permanent and perennial. However, considerable transience is typically observed in the quality of these outflows, with the concentrations of pollutants being highest in the period immediately following initial onset of outflow, with a gradual improvement over time until an asymptotic level of pollution is established (Younger 1997; Wood *et al.* 1999; Gzyl and Banks 2007). Unfortunately, this asymptotic level all too often still exceeds the assimilatory capacity of the receiving water body, so that long-term treatment of the polluted water is required (Younger 1997; Stoertz *et al.* 2001). Predicting the locations, flow rates and quality of mine water outflows is therefore highly desirable if uncontrolled pollution is to be avoided.

Changes in hydrogeology also have effects on the occurrence and migration of asphyxiating and / or explosive mine gases (Hall *et al.* 2005). Hence predictions of post-closure changes are also of interest from a public safety viewpoint (Robinson 2000) as well as from the perspective of public or private bodies that are interested in intercepting abandoned mine methane as an energy resource (Jardine *et al.* 2009; Younger 2014) and for climate change mitigation.

A further incentive for predicting post-closure hydrogeology relates to ground stability: sudden flooding of very shallow workings can lead to weakening of mine supports, leading to surface subsidence (e.g. Smith and Colls 1996). For instance, along the UK's East Coast Main Line railway a few kilometres east of Edinburgh, recovery of regional water levels following the withdrawal of opencast coal mine dewatering (see Younger 2012 for details of the hydrological system) was accompanied by a sudden reactivation of mining subsidence from largely-uncharted shallow coal workings; this prompted a major initiative of grouting old mine voids and relocating a 2 km stretch of railway line (Soudain 2003).

Historically, colliery closure tended to affect individual collieries in a wider coalfield while other collieries with better economic prospects remained in production. Dewatering arrangements generally remained in place to protect working collieries, though over time the financial burden of dewatering a very large area for the benefit of the few remaining productive coal faces would begin to weigh heavily on the economic viability of the last remaining collieries. Eventually, the last remaining colliery in a very extensive coalfield will close, and entire regional dewatering systems will suddenly become superfluous (at least from a mining viewpoint). As these regional systems often control the subsurface drainage of very large areas (commonly many hundreds of square kilometres) the scale of hydrogeological change which their abandonment can cause is very significant (Younger 1993a, 1998a, 1998b). The earliest cases in which large, widely-worked coalfields were finally closed date from the early 1960s, with the abandonment of the Anthracite Field of eastern Pennsylvania (USA) (Ladwig *et al.* 1984) and the Central Fife Coalfield (Scotland) (Henton 1979, 1981). Most of the key features of coalfield abandonment identified above were observed in these early cases of closure, but the lessons had clearly not been learned by the time a wider spate of coalfield closures occurred in North America and Europe in the 1990s. It was only as history repeated itself, and major pollution incidents arose, that regulators began to demand that coal mining companies provide them with predictions of post-closure coalfield hydrogeology, in particular rates of water level rise, future equilibrium water levels and the rates and quality of any future outflows of mine water to rivers and / or aquifers. Beyond environmental protection issues, flooded mine workings may also represent resources, inasmuch as (where water quality permits) they may be used as water reservoirs (Ordoñez *et al.* 2012) and / or as water sources for heat-pump systems providing low-carbon space heating and cooling (e.g. Renz *et al.* 2009; Preene and Younger 2014).

1.2. Existing approaches

A number of modelling approaches have been developed in recent decades to predict the hydrogeological changes that occur after regional coalfield dewatering is abandoned (Adams and Younger 2001). Particular challenges arise in modelling coalfield hydrogeology, due to the non-Darcian nature of flow through mine roadways. In certain cases, this process can be ignored, and standard groundwater modelling packages can be successfully used to simulate abandoned coalfields (e.g. Winters and Capo 2004). However, where the dynamics of flow close to major shafts or drifts must be simulated, Darcian codes fail to adequately represent hydrodynamics (Younger and Adams 1999). For such circumstances, two bespoke types of simulation software have been developed that explicitly account for non-Darcian flow:

(i) Fully physically-based, spatially distributed models, in which a pipe network model domain is routed through a variably-saturated porous medium domain, with intimate coupling of flows within and between the two domains (e.g. Adams and Younger 1997; Hamm *et al.* 2009).

(ii) Simplified semi-distributed models in which flow within large volumes of extensively interconnected workings are represented as 'ponds' (each characterised by a single water level across the entire pond) with localised inter-pond connections being represented by pipe flow equations, calibrated to represent the diameters and roughnesses of mine roadways or other types of connection (e.g. Sherwood and Younger 1997; Banks 2001).

Computer models of both types have been extensively used and documented (e.g. Younger *et al.* 1995; Sherwood and Younger 1997; Burke and Younger 2000; Adams and Younger 2001; Whitworth 2002; Boyaud and Therrien 2004; Winters and Capo 2004; McCoy *et al.* 2006; Gandy and Younger 2007; Hamm *et al.* 2008; Kortas and Younger 2007; Light and Donovan 2015). Post-audits of these applications have shown that they produce useful and realistic results, and that engineering design decisions based on their application have stood the test of time (Younger, 2004; Adams 2014). For instance, the modelling study reported by Gandy and Younger (2007) was undertaken as part of a financial due diligence process during the sale of a profitable mine as a going concern, leading to extension of the life of the mine by eight years.

While such computer-based simulations have proven useful in practice, even the simplest of them are rather expensive to apply, as they require lots of meteorological and geo-spatial data input (e.g. Winters and Capo 2004; Light and Donovan 2015), and even experienced users require many weeks to produce even preliminary outputs. During the late stages of coalfield closure, when only one mine remains in production and it is in financial difficulties, the mine owners typically have neither the time nor money to commission time-consuming and sophisticated numerical modelling studies. In such circumstances, a simplified, lower-cost approach is required to provide regulators with predictions. In the following section, just such an approach is described. The examples used in this paper are drawn predominantly from the coalfields of northern and central England, the general geological setting of which is described by Waters and Davies (2006). Numerous individual studies cited below provide site-specific information on hydrogeological processes and parameters (see especially Younger 1993a, 1994, 1998a, 1998b; Younger and Adams 1999; Adams and Younger 2001).

2. A simple systematic assessment methodology

2.1. Protocol of assessment

Figure 1 sets forth the steps required to assess post-closure hydrogeology of a coalfield where time and financial resources are limited. The concepts underlying each step, and the data sources required for implementing them, are described in detail in Section 2.2.

It should be noted that, depending on circumstance, the individual steps in the overall assessment protocol shown in Figure 1 could be implemented as self-contained exercises. An example of this is given in Section 3.2 below, where Steps 1 through 5 had already been accomplished by other means, so that Step 6 could be implemented as a self-contained exercise.

2.2. Concepts and data sources

2.2.1. Defining the 'Master Seam'

Experience with the flooding of several extensive coalfields in Europe and North America has revealed that hydrogeological changes following a cessation of mine dewatering are controlled by the degree of hydraulic connectivity afforded by old workings (Younger and Adams 1999). In many coalfields, or at least discrete districts within those coalfields, one or two seams will have been worked far more extensively than others, typically because of their thickness (thicker seams being easier to work) and / or their quality (e.g. low-sulphur coals fetch a higher price than high-sulphur coals). Typically, then, there is a '**Master Seam**', the old workings of which provides the bulk of inter-connectivity across the coalfield. For instance, typical Master Seams in some of the larger UK coalfields include: the Dysart Main Seam in the eastern Fife Coalfield (Younger *et al.* 1995); the High Main Seam in the southeast Northumberland Coalfield (Younger 1998a); the Hutton Seam in the northern Durham Coalfield (Younger 1993a; 1994; 1998a); the Barnsley Seam in the eastern Yorkshire Coalfields (Burke and Younger 2000; Gandy and Younger 2007); and the Top Hard Seam in Nottinghamshire (Edwards 1967, pp 96-99). It is common to find that other seams have been worked in relatively isolated patches, but these are almost always connected to the wider coalfield via shafts, roadways and cross-measures that communicate with the regional Master Seam. Once the Master Seam in a given coalfield has been identified, assessment of post-closure hydrogeological changes can proceed.

Identification of the likely points at which outflow will occur from a coalfield after completion of post-closure flooding depends on identifying the topographically lowest zone(s) in which the Master Seam (or locally extensive workings in some seam stratigraphically below the Master Seam, but intimately connected to it) crops out in a river valley and / or is present at shallow depth in a shaft / adit in a river valley (Figure 2). Even where shafts or adits are not recorded, in thick, widely-worked seams they are very commonly present in such riparian outcrop areas, as this is where coal mining typically commenced centuries ago, with miners excavating into coal outcrops. Prediction of the amount of head recovery that must occur before overflow commences is then possible, being the difference in elevation between the deepest unflooded workings in the Master Seam at the time of mine abandonment and the point of lowest topographic outcrop.

2.2.2. Quantifying voidage

The volume of mined voids that remain to flood (the 'voidage') can typically be assessed by mensuration of mine plans, with estimates being included for shallow uncharted workings close to outcrop. A second way to quantify voidage is from records of coal production and waste rock deposition. In many mines, accurate records will only have been kept for the former, but comparison of present-day and historic maps for the area in question should suffice to quantify the latter. When converting coal production records to void space, it is typically assumed that the coal has a uniform in-place ('bank') density; the usual value assumed for UK bituminous coal is 1.3 tonnes per cubic metre (t/m^3), though different coals may display values between 1.2 and 2 t/m^3, depending on their type, rank and porosity.

It is important to note that the voidage gives a minimum figure for the volume of pore space that must be flooded before water level recovery will be complete, because the processes of coal extraction, goaf formation and deformation of the overlying strata inevitably lead to some degree of drainage of water from the newly-fractured overburden above each worked coal seam. Clearly sandstones are more likely to drain than finer-grained lithologies; often the siltstones and mudstones will never fully drain. Furthermore, it is common to find a certain degree of 'perched' saturation persisting in those sandstones that overlie the mudstones in the interburden intervals between subjacent worked seams.

These intricacies mean that, when a system of mine workings finally comes to flood, the water will encounter at least two distinct types of floodable storage space:

- simple unconfined storage in the mine voids and heavily fractured arenaceous overburden, corresponding to largely drained pores available for re-filling
- elastic storage, mainly concentrated in the still-saturated argillaceous / perched arenaceous strata of the inter-seam intervals, in which the main scope for increased storage is restricted to dilation of the pores as the water pressure within them increases – clearly a very marginal process compared to wholesale filling of pores

These distinct processes are reflected in vast differences in the storage coefficient (S; dimensionless), which is effectively the ratio between the water level rise that would occur were the subsurface an open reservoir and the observed water level rise (Δh_o; dimensions: L) reflecting the restriction of voids to pore spaces. Thus for the addition of a given volume (V_A ; L^3) of water per unit surface area (A ; L^2) of an area of workings undergoing flooding:

$$\Delta h_o = \frac{\left[\frac{V_A}{A}\right]}{S} \qquad (1)$$

So for $0.1m^3$ of water accumulating per square metre of an area of workings being flooded, the water level rise in an open reservoir would simply be (V_A / A =) 0.1m; however, if the workings have an S value of 0.1, the observed water level rise (Δh_o) would be 0.1 / 0.1 = 1m. In intervals oof a mined sequence displaying 'unconfined storage' (i.e. where drained pores are available to re-fill) values of S of 0.01 – 0.5 can be expected (with typical values in mined coal-bearing strata around 0.3), whereas in the confined inter-seam intervals values will be considerably less than 0.001, and perhaps as low as 1×10^{-7} (Younger and Adams 1999). Given these marked contrasts in storage coefficient, the same increment of water will cause a far slower rise in water level as the flooding rises through a worked seam than it will through an inter-seam interval. A stepped profile of water level recovery is commonly seen in abandoned coalfields (Younger and Adams 1999); for instance, Kortas and Younger (2007) successfully modelled the historic progress of flooding through a system of widely-worked coal seams in southern County Durham, UK, accounting for the contrast in storage between worked seam intervals and largely intact interburden intervals.

Nevertheless, as the rate of rise is so much faster in the inter-seam intervals, a conservative estimate of the time likely to be required for full water level recovery (i.e. erring on the side of rapidity) can be obtained by simply calculating the time required to full the extracted voids alone, neglecting the inter-seam intervals.

2.2.3. Water inflow rates

Of course, the rate of water level recovery in the coalfield is not solely a function of voidage: the rate of water inflow to the mined system is also a key control. While sophisticated modelling packages may calculate water inflow rate from first principles from measured rainfall data (e.g. Sherwood and Younger 1997; Adams and Younger 2001), a maximum rate of inflow actually encountered in the workings tends to be readily obtainable from mine operators, or from records of pumped discharges kept by regulators. In interpreting these records, it is important to take into account any water that was artificially imported to the mine for process purposes: in the drier mines, the bulk of the water pumped from the mine may well have been introduced artificially from surface (e.g. via pipelines serving dust-suppression equipment) and therefore does not represent incoming ground water at all. Having eliminated the imported component, the incoming ground water can be quantified. It is important to appreciate that, in most deep coal mines, measurement of mine water flow rates is not normally undertaken using high-precision hydrometric techniques; rather, the run-times of pumps are simply multiplied by the rated capacity of the pump (adjusted according to the head against which it was operating). As pumps rarely run at their full rated capacity, due to mechanical inefficiencies and variations in pumping head, such flow estimates tend to be over-estimations. This in turn means that water level recovery rates based on them tend to be exaggerated. From a regulatory perspective this is far preferable to over-estimating the time recovery will take, as the latter could lead to overflow occurring before treatment facilities at surface have been commissioned.

Having obtained an estimate of the maximum rate of water inflow to the workings, an adjustment may be contemplated to account for the widespread observation that the rate of water inflow decreases as the head difference between the interior of the mine and the surrounding rock mass decreases during water level recovery (see Banks 2001; Younger *et al.* 2002). That water inflow to a pumped void is head-dependent is a universal principle in hydrogeology: it is the theoretical basis for the many mathematical expressions that correlate the rate of pumping with the magnitude of drawdown in a pumping well (e.g. Theis 1935). In many coalfields, the very deepest mine waters are very saline, corresponding to very ancient ground waters trapped in the coals seams and associated clastic sediments. It is reasonable to assume that these very deep-seated waters will never have sufficient driving head to persist as an important element of inflow when water levels have recovered to surface and are decanting under gravity. (An important exception might be where continued pumping of water from a deep shaft is used to prevent final water level recovery, in which case deep saline water can be induced to rise up to the pumps (Younger 1998); this is currently the case, for instance, in the pumping stations operated by the Coal Authority at Dawdon (County Durham) and Bates (Northumberland) on the coast of north-east England; Younger *et al.* 2015). Waters with chemical signatures indicative of relatively fresh, recent recharge from the surface environment are more likely to persist as head-independent sources of inflow, particularly where they originate as rain-fed recharge to outcrop areas lying topographically higher than the lowest outcrop of the Master Seam. Whatever the case, the head-dependent sources of inflow will all be progressively eliminated from the inventory of total flow entering the workings as their source strata are submerged. Experience in various exposed coalfields in the UK suggests that the head-independent component of inflow typically amounts to 60% to 70% of the peak inflow rate represented by the maximum dewatering rate before closure.

2.2.4. Estimation of equilibrium hydraulic gradient

Once water level recovery is complete, with outflow to surface and /or overlying aquifers from one or more decant routes, a final hydraulic task is assessing the rest water level across the wider coalfield area. This is needed in order to check whether outflow will be restricted to the lowest-lying outcrop of the Master Seam (or locally interconnected seams; cf Figure 2), or whether post-recovery water levels will be high enough to also give rise to other (usually less vigorous) outflows from shafts or drifts at higher elevations. For instance, in the central Fife Coalfield in Scotland, the closure of the last coal mine (Minto Colliery) in 1967 led to a nine-year period of water level recovery followed by sequential onset of outflows from several former mine entrances to the nearby River Ore, commencing at the most downstream position (New Carden; UK national grid reference NT 233961; elevation 60m above Ordnance Datum (aOD, i.e. the UK standard mean sea level) in December 1976, and culminating with outflows from the Minto No 2 shaft upstream (NT 204949; 70m aOD) about a month later (Younger 2001). The head difference between the easternmost and westernmost outflows is ~ 10 metres, and this occurs over a lateral distance of about 3200 m (as the crow flies; the actual ground water flow paths between the two will be tortuous and therefore longer), so that the equilibrium hydraulic gradient in the abandoned coalfield is on the order of 10 / 3200 = 3×10^{-3}.

Where sophisticated distributed models of water level recovery are used, such equilibrium hydraulic gradients will be calculated automatically, as part of the solution of the flow field. However, in the absence of this, a simplified assessment approach is needed. To a first approximation this can be handled by establishing the level of the lowest outflow, as explained above, and then doing a sensitivity analysis of the likely water levels at other, higher mine entrances using a range of hydraulic gradients measured in large, fully recovered coalfields. Generally, hydraulic gradients in flooded mine workings are rather low in comparison to natural aquifers, due to the very high effective permeability of major mine roadways. Hence at local scale, hydraulic gradients along a given roadway are often immeasurably small (e.g. Aljoe 1994). It is typically only over distances of several kilometres that appreciable hydraulic gradients become detectable. (The only common exceptions to this occur where there is a substantial partial blockage in one of the principal mine roadways, which can lead to local impoundment of head).

Calculation of hydraulic gradient (i ; dimensionless) is straightforward: the difference in hydraulic head between the two points is divided by the distance between them. For instance, for if a head difference of 2.74m is measured between two hydraulically inter-connected points 3,400m apart, then $I = 2.74 / 3{,}400 = 8 \times 10^{-4}$. Very few values of i are quoted in the literature, however. So in order to provide a range of suitable gradients, an analysis has been made of mine water levels in the main Northumberland Coalfield (UK), which is now recovered to a position very close to sea level (Figure 3). Indeed, following regional recovery of mine water levels from the mid-1990s to the early 2000s, a modest natural outflow has become established into a tidal stream on the coast at Seaton Sluice (NZ 334 764). Meanwhile the bulk of the outflow from the coalfield is brought to surface from a shaft of the former Bates Colliery (NZ 306 823), where a large pump-and-treat operation is used to remove iron from the water before disposal to the sea. The pumping head at Bates is kept to a minimum to minimise electricity consumption, so that the coalfield as a whole is now at virtually its natural equilibrium water level. Ground water levels are measured at an array of boreholes and disused mine shafts disposed radially inland around the Seaton Sluice discharge and the Bates pumping shaft

(Figure 3), and these have been used to calculate apparent linear hydraulic gradients (i.e. as the crow flies, not via the tortuous mine water flow paths) in the recovered coalfield, using the simple method exemplified above. Table 1 summarises the measured values of hydraulic gradient (*i*) between several pairs of points shown on Figure 3, using data from January 2014 (a month in which water levels in most measurement points lie close to their average values). It is found that apparent hydraulic gradients range from 1×10^{-4} up to 1×10^{-3}, with a mean of 6×10^{-4}. It is noted that the apparent hydraulic gradient in the central Fife Coalfield (3×10^{-3}) marginally exceeds the upper bound value for Northumberland. There are two likely explanations for this. Firstly, the workings in the Fife area do not extend very far to the east of New Carden, so that a degree of impoundment of levels occurs there. Furthermore, the magnitude of the hydraulic gradient is also affected by the rate of water inflow, which because of orographic rainfall patterns is likely to be greatest in exposed coalfields that extend into upland areas (e.g. in Fife the mined catchment rises to more than 300m above sea level, whereas the Northumberland coalfield entirely lies below 80 m aOD). In concealed coalfields, where the mined strata are completely covered by younger strata hosting their own independent hydrogeological systems, the rate of water inflow is likely to be far lower than in the rain-fed case of the exposed coalfields, so that equilibrium hydraulic gradients are more likely to fall close to the lower end of the range observed in Northumberland.

2.2.5. Predicting water quality

Prediction of post-recovery water quality is very challenging (Younger 1997, 2000); it is certainly not amenable to precise, quantitative simulation, so any estimate must be presented in a manner that acknowledges the irreducible uncertainties. In broad terms, the acidity and iron content of the mine water flowing from a coalfield following completion of water level recovery will reflect the sulphur content of the Master Seam, and of any other widely-worked seams. This is because total sulphur content is a good proxy for total pyrite content, at least at higher total sulphur contents where the correlation matters most (Casagrande 1987). This is good news, as typical Master Seams will seldom be high-sulphur (though in some smaller coalfields they certainly are; see, for instance, Younger and Thorn 2006). Nevertheless, accurate prediction of a wide range of parameters is beyond present capabilities, and the only simplified prediction protocol produced to date is for total iron (Younger 2000). The peak iron concentration, in the immediate aftermath of water level equilibration, can be predicted, along with the rate of decrease in iron concentrations to a long-term equilibrium value (Younger 1997). A flowchart to guide these evaluations is presented by Younger (2000), and a thorough example of the application of this approach to the Upper Silesian Coal Basin in Poland is presented by Gzyl and Banks (2007).

3. Case study of application: the North Nottinghamshire / Derbyshire Coalfield

The North Nottinghamshire / Derbyshire Coalfield (NNDC) has been worked intensively since the early 1800s, with the zones of active mining gradually progressing from the outcrop area in the west into the concealed coalfield in the east, where the Coal Measures are overlain by sedimentary strata of Permo-Triassic age (Edwards 1967). The last coal mine in the coalfield (Thoresby) entered its final closure period in 2015, so a simple, low-cost analysis of the future hydrogeology of the coalfield is timely. The application of the protocol of Figure 1 to this coalfield is now summarised, by way of a worked example.

Step 1 – Identification of the Master Seam. There is no doubt that the Master Seam in the NNDC is the Top Hard Seam, as this is by far the most widely worked seam in the coalfield (Edwards 1967), having been extracted almost continuously from outcrop down-dip to the most modern mines, such as Clipstone (closed 2003), Welbeck (closed 2010) and Thoresby (Figure 4). Although the workings of these deepest mines were very dry, they are connected up-dip to an extensively inter-connected body of old workings which receive considerable recharge from rainfall and surface runoff. As long as the deepest mines remained in production, this recharge was intercepted where it accumulates in shallower workings and pumped to the surface for disposal to nearby watercourses. Over the years, many disused many shafts have been used for this purpose in the NNDC, though in recent years pumping was concentrated in the shafts at Williamthorpe, Creswell and Langwith (Figure 4). By the end of 2014, only Williamthorpe was in regular use.

Examination of mine plans and the response of water levels to changes in pumping patterns revealed that two subsurface drainage areas existed in the NNDC: a southern drainage area (shaded dark grey on Figure 4) extending from Williamthorpe to Clipstone Colliery and a northern drainage area (shaded light grey on Figure 4) extending from Blacks to Thoresby, via Creswell and Welbeck. Extensive mined connections within the Top Hard Master Seam ensure pervasive hydraulic connectivity within these two drainage areas, although lateral connections between the two are rather limited, with a suspected connection from Langwith to Shirebrook, and a deep connection via a locomotive roadway from Clipstone to Thoresby. By the time the last coal production in the NNDC took place (at Thoresby in 2015) there was still no evidence of any flow along the latter connection, which suggests that the sustained pumping at around 75 L/s at Williamthorpe had successfully prevented down-dip migration of large quantities of water through the southern drainage area. This pumping rate achieved a mine water level at Williamthorpe of around 150m below OD.

Mine water migration through the northern drainage area through the HTT sub-system was previously controlled by pumping stations at Duckmanton, Hartington, Langwith and Creswell. Langwith formerly pumped a fairly steady 7.5 L/s, though lesser rates were pumped until 2013 when pumping ceased. An average of 15 L/s was pumped at Creswell until March 2010, when pumping was suspended. Water levels in the Creswell shaft initially rose quite sharply, but soon settled out at a level very similar to that at Langwith, and examination of mine plans suggests that this steady level mainly reflects establishment of decant eastwards from Creswell and Langwith through mined connections at around 220m BOD towards the extensive, unflooded working of Welbeck Colliery (which closed only in May 2010). Some decant to the southern drainage area, towards Shirebrook, may also contribute to this steadying of water level.

Step 2: Identify outflow features. Having identified the Top Hard Seam as the Master Seam in the NNDC, identification of the lowest-lying point on its outcrop suggests that the most likely future gravitational decant point to surface in this coalfield will be in the vicinity of the zone at which the River Rother crosses the seam outcrop. Mine records indicate that this occurs just north of Staveley. The most likely scenario is that outflow will occur from the well-engineered former pumping shaft at Hartington (SK 43398 75377; Figure 4), though it might also occur via other old mine entrance features that are inferred to be present in the adjoining riparian seam outcrop zone. The likely decant lies at about 50m aOD, and this represents a key datum in assessing the overall process of mine water recovery, as establishment of outflow there would likely put a halt to further water level rise ('rebound') throughout the coalfield.

Step 3: Quantify voidage. In the case of the NNDC, mine plans are excellent and publicly available from the UK Coal Authority. Measurement of mine plans for the Top Hard seams yields an estimated unflooded voidage of around 51.385 Mm^3 (corresponding to the maximum extent of mining in the NNDC, in 2015).

Step 4: Quantify water inflow rates. The sum of the recently-pumped quantities listed under Step 1 above (97.5 L/s) is an under-estimate of the total amount of water entering the NNDC: evidence from earlier periods of mining suggests that a total inflow on the order of 135 L/s is more realistic. Of this total, the vast bulk arises in near-outcrop locations, where infiltration of rainfall is presumably augmented by significant interception of surface runoff by shallow old workings and permeable opencast backfill (which is extensive across the outcrop of the Coal Measures in this region). In the deeper mines to the east, such as Welbeck, Clipstone and Thoresby, water sourced within the workings themselves is very scarce (typically less than 1 L/s in each of these mines) and is identified on chemical grounds as being native to the Coal Measures strata themselves. Such low inflows to deep longwall workings at comparable depths are well documented in similar settings in the UK (e.g. in the Selby Coalfield; Younger 2016). The overall picture which emerges of the NNDC hydrogeological system is of a large volume of largely dry / only partially flooded mine voids in the east (around Thoresby, Welbeck and Clipstone), down-dip from variably flooded voids between the outcrop and the Creswell-Langwith axis. This provides the starting point for assessing future recovery of mine water levels throughout the NNDC.

The crudest analysis of rebound would simply assume that the entire estimated total water inflow for the NNDC (i.e. 135 L/s) will persist throughout the rebound process. This is unlikely however, as a significant component of the total inflow is likely to be head-dependent. This would certainly be expected to apply to the very saline mine waters formerly pumped at Creswell and Langwith, and those locally encountered (but never pumped to bank) within Welbeck, Clipstone and Thoresby. Other head-dependent sources will also exist up-dip from Creswell / Langwith, though *a priori* identification of them is more equivocal than for the very saline waters. Before completion of rebound it is not possible to accurately estimate what proportion of the total water inventory is head-dependent, though accepting figures from similar coalfields (section 2.2.3), about 60 to 70% of the total inflow rate can be expected to persist after completion of rebound. This is estimated at 80 to 95 L/s, which corresponds to only 5 to 20 L/s more than was pumped until very recently at Williamthorpe.

Step 5: Quantify rate of water levels rise. If the voidage estimated in Step 3 is divided by the total estimated water inflow rate of 135 L/s, the time to onset of surface decant is estimated at about 12 years. Various modifications to this calculation can be performed to take account of the various factors discussed above. For instance, if the likely decline in head-dependent inflows over time is taken into account, and it is assumed that these will have amounted to 40% of the former pumping rate by completion of rebound, then the *effective* inflow rate over the full period of rebound is a median between the two figures, i.e. 0.8 x 135 L/s = 108 L/s. This yields an estimated total rebound time of 15 years. Further modifications could be made, such as calculating a net storage coefficient for rebound for various levels in the coalfield; however, this would introduce a degree of complexity that would soon exceed the scope of the simple low-cost approach presented here. In any case, Moreover, as such calculations would still use depth-zoned weighted averages of the storage coefficient, varying from as much as 3×10^{-1} for zones of old workings to as little as around 1×10^{-7}

for undisturbed strata far above the workings (section 2.2.2), the overall tendency would be for the far higher values of the worked zones to swamp the contribution from the undisturbed strata. In other words, the storage coefficient attributable to the worked voids would in any case dominate the far more elaborate calculations, and it is therefore anticipated that similar total times to completion of rebound to those quoted above would be obtained. If experiences in similar large coalfields with comparable inflow rates (e.g. the main part of the Durham Coalfield) are compared with these estimates then a timescale of 12 to 15 years for total rebound leading to decant at Hartington seems reasonable.

Step 6: Estimate post-recovery water levels. If the entire post-rebound outflow from the NNDC does indeed occur in the exposed coalfield (at Hartington or elsewhere) then the deeper workings of the concealed coalfield will become largely stagnant. However, if post-rebound hydraulic heads in the exposed coalfield are in excess of those of overlying aquifers, or even of the ground surface elevation, then if permeable pathways to either (or both) exist, some proportion of this total outflow rate could conceivably be released to aquifers or rivers in the concealed coalfield. In that case a lesser outflow would be expected at Hartington, and attention would need to be paid to mine water outflow at other sites. The two key issues would be establishment of:

(i) surface overflows from the lowest-lying shaft(s) in the concealed coalfield area, and / or
(ii) outflows to the overlying Permo-Triassic freshwater aquifers

Assessment of both of these possibilities is achieved by calculating the maximum likely head at a given distance from Hartington using a range of plausible post-rebound hydraulic gradients (see section 2.2.4 and Table 1). Shaft collars at all of the collieries outside the riparian corridor of the River Rother are all sufficiently elevated that surface outflows seem highly unlikely under credible post-rebound hydraulic gradients.

As regards the Permo-Triassic aquifers, all shafts in the concealed coalfield (i.e. those shafts shown as lying east of the ‘Base of Permian’ trace on Figure 4) pass through the lowermost of these (the Magnesian Limestones), whereas only the most easterly shafts (e.g. Welbeck and Thoresby; Figure 4) also pass through the overlying Sherwood Sandstones Aquifer. At some of the shafts in the concealed coalfield, even assuming a totally flat water level after rebound the we would still expect post-rebound mine water levels to be higher than the base elevation of one or more of the Permo-Triassic aquifers. However, this does not mean that outflow of mine water to the aquifers would occur: there are two other prerequisites before that becomes a possibility. The first is that the head of mine water must exceed the head of ground water in the aquifer. A general indication of ground water levels in these aquifers is provided by piezometric maps produced from time to time by the British Geological Survey and the Environment Agency. Thus the published 1:100,000 scale hydrogeological map of the northern East Midlands (IGS 1981) indicates that groundwater levels in the Magnesian Limestones Aquifer are around 75 mAOD at Langwith and 80m AOD at Creswell. On this basis, there is no possibility of post-rebound outflow into the aquifer from the Langwith and Creswell mines; on the contrary, if any hydraulic connections to the overlying aquifers do exist in those mines, the Magnesian Limestone would be delivering head-independent inflows to the flooded coal workings in perpetuity. Further east, ground water levels in the Sherwood Sandstones Aquifer in the vicinity of Thoresby and Welbeck are typically close to 40m AOD (IGS 1981). As this is lower even than the predicted rest water level at Hartington (some 21.6 km to the west), there could indeed be sufficient head after completion of rebound to give rise to mine water outflows into the aquifer. However, this could only occur if permeable pathways existed. Two possible pathways merit consideration:

(a) vertical upflow from the flooded workings through the intervening unmined strata to the base of the Permian, and
(b) direct outflow from the shafts where these pass through the aquifers.

With regard to potential pathway (a), the experience of water management within Thoresby Colliery is highly instructive. The extremely low water make of Thoresby Colliery (averaging < 0.4 L/s) reflects the thickness and low permeability of the Coal Measures mudstones and siltstones that lie between the Thoresby workings and the base of the Permian. The shallowest worked seam at Thoresby, the High Hazles, lies some 234m below the base of the Permo-Triassic strata; this is more than twice the vertical stand-off recommended in UK coal mining settings to ensure that mining does not induce hydraulic connectivity with overlying aquifers (Orchard 1975). Even the extensive fracturing and potential for under-drainage induced by longwall coal extraction proved incapable of inducing significant inflows from these strata. This is all the more impressive when it is remembered that two fully saturated aquifers overlie these low-permeability strata, and that the potential driving head to the drained workings was in excess of 480m.

As regards potential pathway (b), the shafts at Welbeck were backfilled with compacted, low-permeability materials, and similar plans for the Thoresby shafts have been agreed by the Environment Agency. It thus seems that pathway (b) will not be viable. It should be noted that other mines closed long ago may not have such well-constructed shaft fills, and in some cases might have other connections to the Permo-Triassic sequence, as has been discussed for the adjoining South Nottinghamshire Coalfield by Robins *et al.* (2002). However, investigation of that possibility is beyond the scope of the rapid, low-cost assessment methodology developed here; application of more complex distributed models (Adams and Younger 2001), coupled to detailed geological models, would be needed to make such an assessment.

Step 7: Estimate post-closure water quality. As the Top Hard seam is low-sulphur, the peak iron concentrations from any future outflow are not expected to exceed 70 mg/L, exponentially declining to an asymptotic concentration of around 7 mg/L within a few decades of the onset of outflow in the Hartington area. These concentrations are comfortably within the range that is routinely handled in existing mine water treatment systems in the UK.

4. After the deluge: future use of coalfield hydrogeological models

The approach demonstrated in this paper has been developed for the purpose of predicting post-closure hydrogeological behaviour of abandoned coalfields. However, the concepts and data sources outline here could also be adapted for other purposes, such as the design of coalfield monitoring and modelling exercises during the years following mine closure. The insights into system behaviour gained from such exercises could well be valuable in future re-use of flooded voids as resources, for instance as water resource reservoirs (Ordoñez *et al.* 2012) or as water sources for heat recovery / disposal as part of low-carbon heating systems (e.g. Renz *et al.* 2009; Preene and Younger 2014).

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List of Figures

1. Flow chart for the assessment protocol for post-closure hydrogeological evolution of abandoned coalfields.

2. Typical mine water outflow features in a river valley (red arrows), where a master seam reaches its lowest point of outcrop (often accessed via an adit), and / or is connected to a point lower than its lowest outcrop via a connected locally-worked seam, and / or is connected to surface via an abandoned shaft.

3. Sketch map of the eastern coastal section of the main Northumberland Coalfield, UK, showing mine water level monitoring sites discussed in the text and in Table 1. (Mine water levels as at January 2014, courtesy of the Coal Authority). The topography inland is essentially flat, sloping gently towards the coast from around 60m above sea level in the west to around 10m at the coastline, where shallow cliffs and sand dunes drop to the beach. Note that the virtually the entire area shown in this map has been undermined on multiple horizons, both onshore and offshore.

4. The North Nottinghamshire / Derbyshire Coalfield (NNDC), central England. (a) Sketch map showing locations of principal localities mentioned in the text. The dark shaded area is the southern drainage area and the lighter shaded area is the northern drainage area, as described in section 3. Shaded areas correspond to areas underlain by NNDC coal mine workings, principally in the Top Hard Seam (Edwards 1967). The unshaded area to the north is the southern fringe of the South Yorkshire Coalfield, which is essentially hydraulically isolated from the NNDC and is not considered in this paper. (b) Simplified W-E geological cross-section along the line indicated on map. Surface locations: Wi = Williamthorpe; Sh = Shirebrook; Th = Thoresby. Permian strata: BB&LPM = Basal Breccia and Lower Permian Marl; LML =- Lower Magnesian Limestone; MPM = Middle Permian Marl; UML = Upper Magnesian Limestone; UPM = Upper Permian Marl.

Table 1 – Typical apparent hydraulic gradients for a fully-rebounded coalfield. Values calculated (using straight line distances) between various pairs of adjoining mine water level measurement stations in the main coalfield of Northumberland (for locations see Figure 3).

Line of gradient	**Distance (m)**	**Head difference (m)**	**Hydraulic gradient (*i*) (dimensionless)**
Seaton Delaval to Seaton Sluice Discharge	3,400	2.74	8×10^{-4}
Astley Arms Borehole to Seaton Sluice Discharge	850	0.92	1×10^{-3}
New Delaval to Seaton Sluice Discharge	5,600	3.29	6×10^{-4}
Crofton Borehole to Bates No 2 Shaft	1,750	0.17	1×10^{-4}
New Delaval to Bates No 2 Shaft	2,650	3.14	1×10^{-3}
Bedlington ‘A’ Shaft to Bates No 2 Shaft	3,400	2.44	7×10^{-4}
Choppington ‘A’ Shaft to Bates No 2 Shaft	5,750	2.4	4×10^{-4}
North Seaton to Bates No 2 Shaft	3,950	0.83	2×10^{-4}

STEP 1: MASTER SEAM GEOMETRY

Define the Master Seam in the coalfield and identify the principal interconnections between discrete volumes of workings.

(*for guidance see Section 2.1.1*)

STEP 2: IDENTIFY OUTFLOW FEATURES

Locate the lowest topographic point at which the Master Seam (or a well-connected underlying seam) crops out in a river valley (or is connected to it via a shaft / drift).

(*for guidance see Section 2.1.1 and Younger & Adams, 1999*)

STEP 3: QUANTIFY VOIDAGE

Either by measuring mine plans or studying coal production records etc, identify the volume of empty voids that remain to be flooded.

(*for guidance see Section 2.1.2*)

STEP 4: QUANTIFY WATER INFLOW RATES

The maximum rate of inflow will correspond to peak dewatering pumping rate before closure (adjusted to eliminate any known imported water); adjust as necessary to allow for loss of head-dependent components as the water level rises.

(*for guidance see Section 2.1.3 and Younger* et al. *2002)*

STEP 5: RATE OF WATER LEVEL RISE

Use the information from Steps 3 and 4 to calculate how long it will take for water levels to reach the equilibrium level defined by outflow from the Master Seam (from Step 2). At its simplest, this requires simply the division of total voidage by maximum flow rate, yielding a minimum time to equilibration of water levels. More sophisticated analysis can be made by calculating sequential rates of filling for worked seam intervals and inter-seam intervals.

(for guidance see Section 2.1.2 and Younger 1993b)

STEP 6: ESTIMATE POST-RECOVERY WATER LEVELS

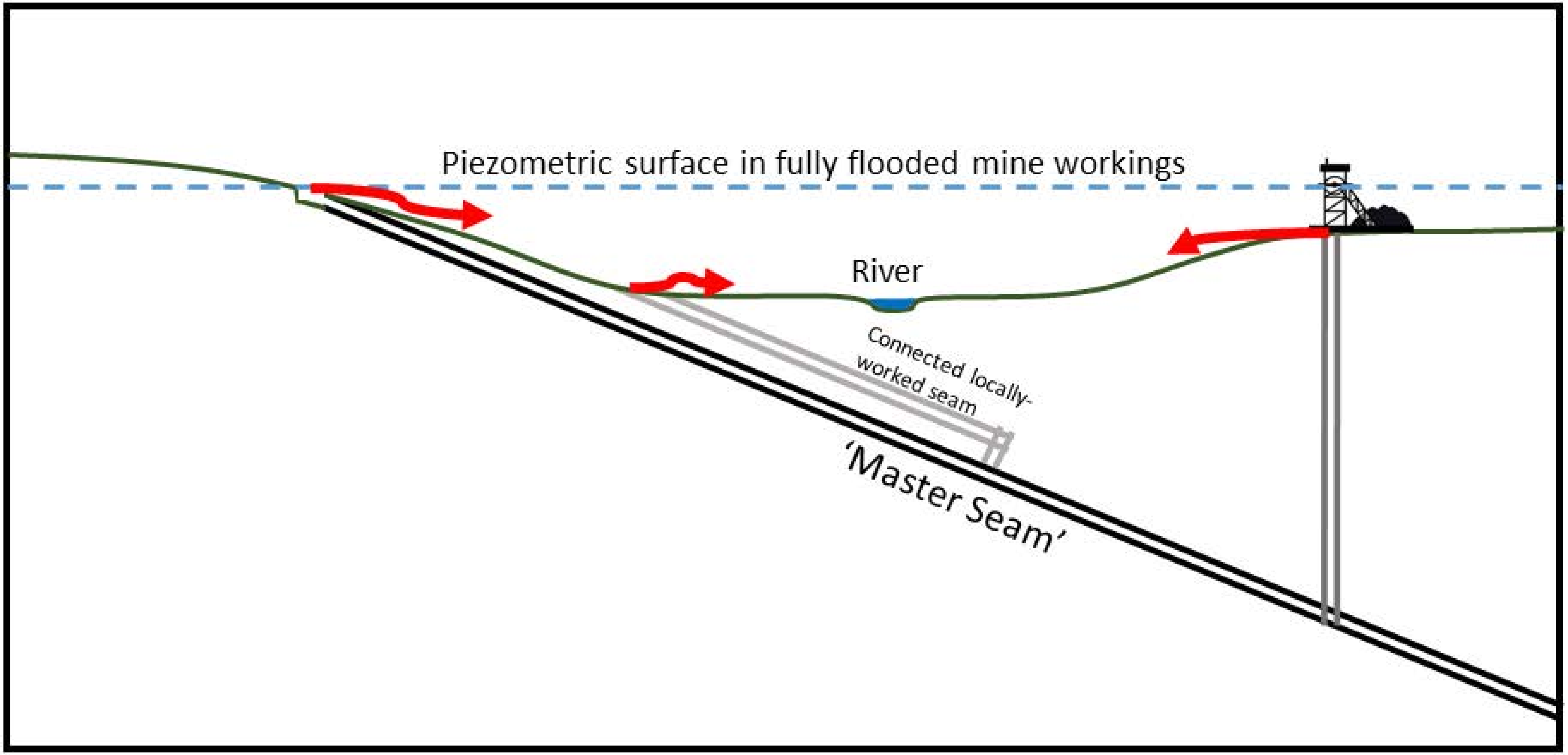
Use the observed range of apparent hydraulic gradients from recovered coalfields to estimate the water level at points within the flooded system distant from the outflow from the Master Seam (from Step 2). This requires assumption of a gradient value, and extrapolation from the Master Seam outflow point to any other point within the mine system at a known distance.

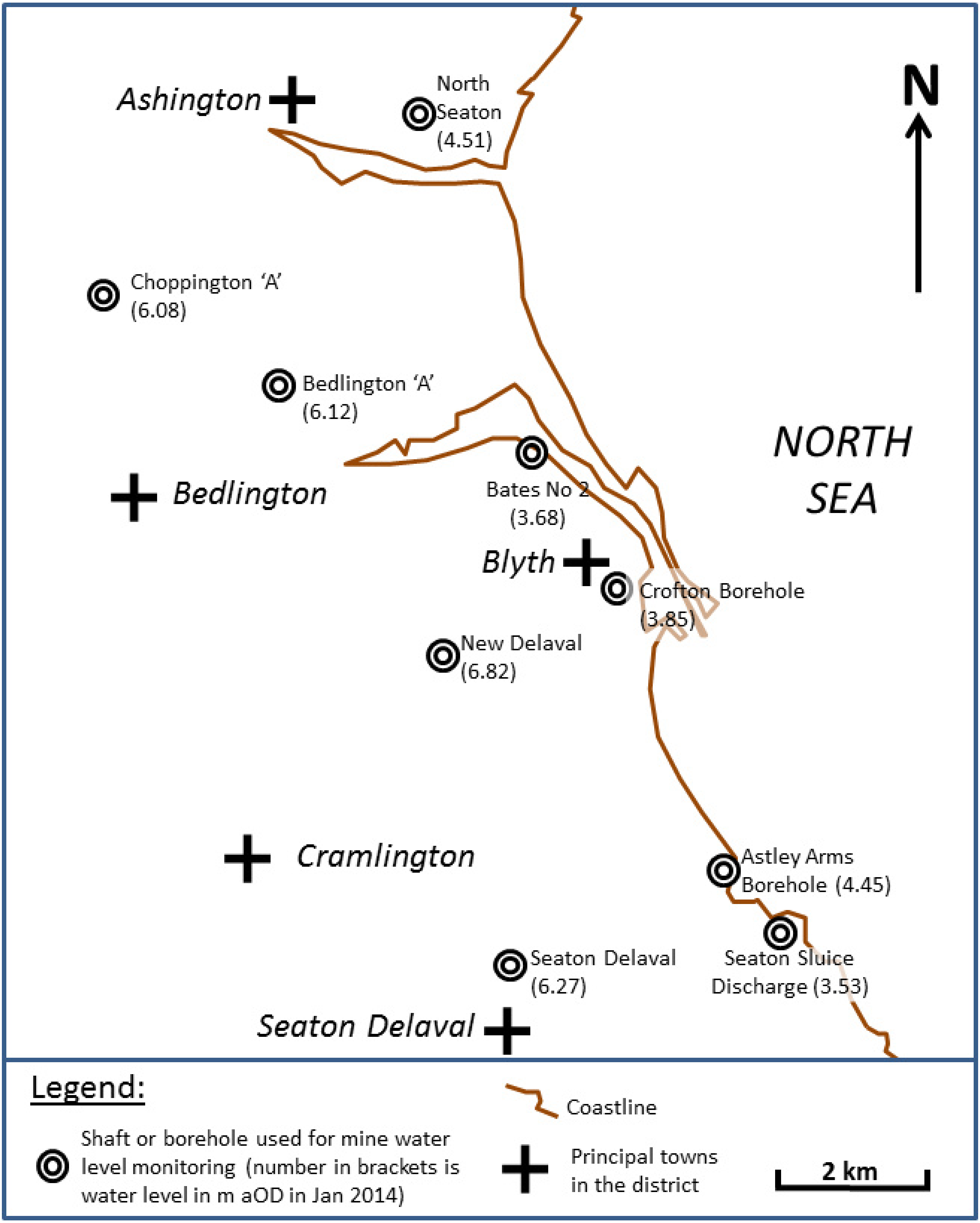
(for guidance see Section 2.1.4, see also Younger & Adams 1999, and Younger 1993b)

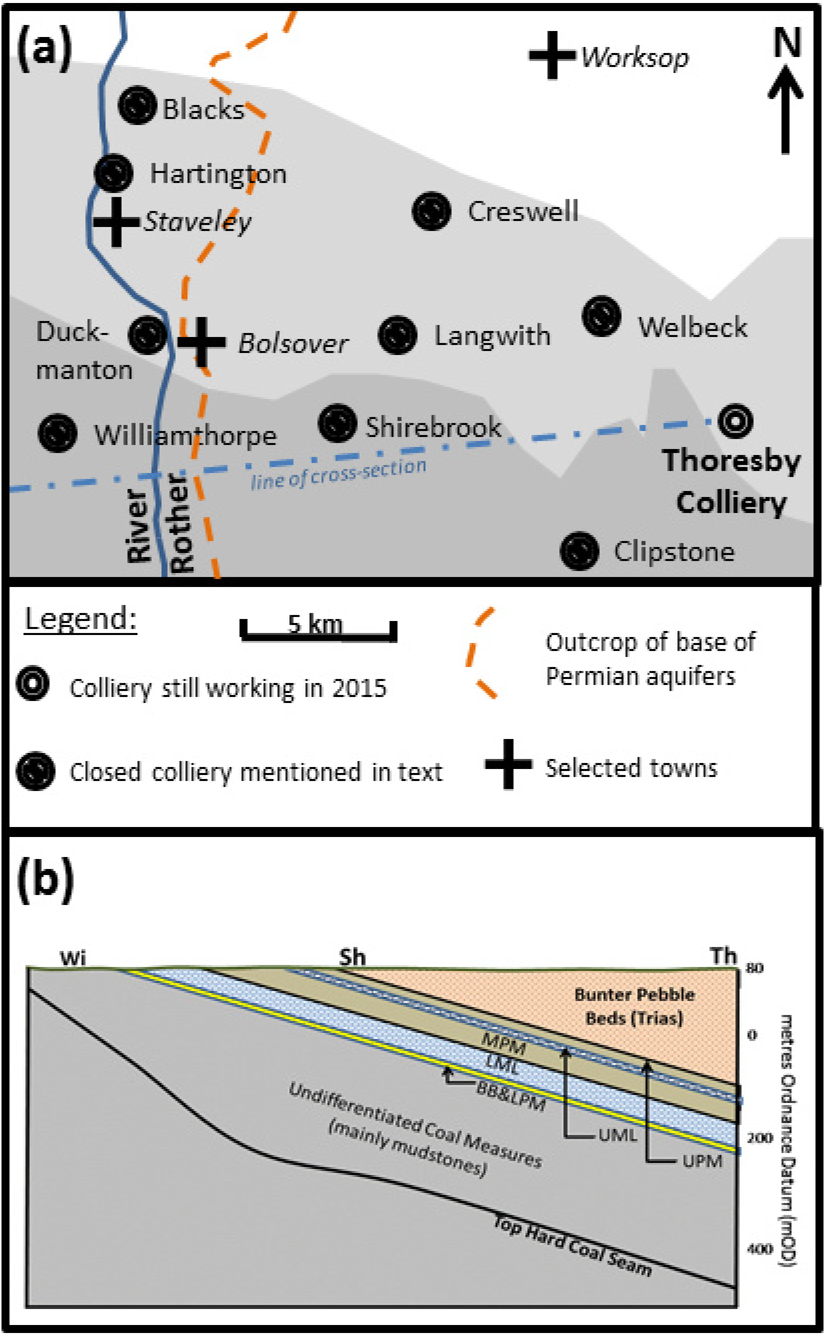
STEP 7: ESTIMATE POST-RECOVERY WATER QUALITY

Use information on seam sulphur content and the estimated total duration of water level recovery (Step 5) to estimate likely peak and long-term pollutant concentrations.

(for guidance see Section 2.1.5 and Younger 2000)


Piezometric surface in fully flooded mine workings
River
Connected locally-worked seam
'Master Seam'


N
Ashington
North Seaton (4.51)
Choppington 'A' (6.08)
Bedlington 'A' (6.12)
Bedlington
Bates No 2 (3.68)
NORTH SEA
Blyth
Crofton Borehole (3.85)
New Delaval (6.82)
Cramlington
Astley Arms Borehole (4.45)
Seaton Sluice Discharge (3.53)
Seaton Delaval (6.27)
Seaton Delaval
Legend:
Coastline
Shaft or borehole used for mine water level monitoring (number in brackets is water level in m aOD in Jan 2014)
Principal towns in the district
2 km


(a)
Worksop
N
Blacks
Hartington
Staveley
Creswell
Duck-
manton
Bolsover
Langwith
Welbeck
Williamthorpe
Shirebrook
Thoresby
Colliery
line of cross-section
River
Rother
Clipstone
Legend:
5 km
Outcrop of base of
Permian aquifers
Colliery still working in 2015
Closed colliery mentioned in text
Selected towns
(b)
Wi
Sh
Th
80
0
200
400
metres Ordnance Datum (mOD)
Bunter Pebble
Beds (Trias)
MPM
LML
BB&LPM
UML
UPM
Undifferentiated Coal Measures
(mainly mudstones)
Top Hard Coal Seam