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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

Paul L. Younger

School of Engineering, University of Glasgow, Glasgow, G23 5EB, Scotland, UK

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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.

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, , 1998a,b). 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

E-mail address: paul.younger@glasgow.ac.uk.

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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, b). 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., 2008).
(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 8 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, b; Younger and Adams, 1999; Adams and Younger, 2001).