'Making water': the hydrogeological adventures of Britain's early mining engineers

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Abstract: The earliest detailed technical descriptions of British mining practices still in existence (which date from the late 17th and early 18th centuries) dedicate many paragraphs to the problems posed by the unwanted ingress of ground water into underground workings. Excessive water in working areas seriously hinders production. More importantly, sudden inrushes of ground water to underground workings are a significant mortal hazard. In view of the problems experienced with water ingress to workings, the main preoccupations of the early mining engineers were utterly practical, focusing on the efficient removal of water which could not be prevented from entering the workings (by simple bailing, by adit drainage or by pumping), and on efforts to minimize water ingress in the first place (by the use of tubbing in shafts and the use of rock barriers and dams in working areas). Occasionally, the mining engineers took time to reflect upon the origins of the water they encountered in their work. In their writings we find some of the earliest accurate conceptualizations of issues of ground water origin, driving heads, hydraulic gradients (including vertical upward gradients) and natural heterogeneities in water quality. So successful were these early mining engineers in their endeavours that they bequeathed most of the technological basis for the development of large-scale public-supply ground water abstractions, and much of the basis for the geotechnical control of ground water during construction projects, from about 1820 onwards. By the late 19th Century, mining engineers concerned with ground water management became gradually isolated once more within their own specialist domain, where they went on to develop a vernacular hydrogeology of their own, replete with its own key concepts and vocabulary. Nevertheless, occasional interchanges of experience between mining and the water industry have continued to enrich both sectors down to the present day.

Mines do not only produce minerals, they also 'make water'. In mining terminology, the total water yield of a mine or a specific district of a mine is known as its 'water make', and the mine or district is said to be 'making water'. Most of the water being 'made' by the mine is, of course, ground water. Excessive water makes have long been the enemy of miners. In responding to this enemy, mining engineers accidentally became pioneers in the field of ground water engineering. As a by-product of their efforts in relation to water management, the early mining engineers inadvertently laid the foundations for much of the modern water industry, so that in a very real sense the practice of mining hydrogeology can be said to have been 'the making of water' as a technologically advanced industry. The miner's struggle with water also paved the conceptual and technological way for much of modern geotechnical practice in the control of ground water in the construction industry. While a full account of the many ways in which mining engineering fathered both modern water engineering and modern ground water control practices would require a book in itself, this paper has the more modest aim of drawing together some of the key experiences of the early mining engineers with ground water and what they made of them in both practical and scientific terms. It should be noted that the coverage of this paper is largely restricted to events and scientific developments which occurred prior to 1913 (the year which marked the peak of production in most major British coalfields), with only a few minor references to more recent events which happen to shed light on earlier historical developments. The paper also ignores those pre-1900 mining developments which were undertaken to deliberately stimulate ground water movement, with the purpose of facilitating brine production in the Cheshire salt basins; a recent review of the hydrogeological setting and specific mining practices of that area has been presented by Cooper (2002).

Ground water problems in mining

'. . . How silently in former ages all this water had found its way,
perhaps drop by drop, into the stony reservoirs!
How silently it had lain there, under solid strata,
no one suspecting its existence!
But now at length, man must trouble the peaceful waters –
must rudely unseal their rocky caskets, and, lo!
He shall have no more peace for them –
no more quiet shall there be in that vicinity.

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The fountains of the deep in the hollow places of the earth
have been broken up by rude hands, and they shall now pour forth unceasingly
thousands of gallons after thousands of gallons,
and these, too, minute by minute, – torrent after torrent – rush, rush, rush!
Ah, foolish man! what hast thou done,
evoking a Spirit of the floods thou canst not lay? . . .'
(Leifchild 1853)

While water has long been of benefit to certain aspects of mining operations, by providing an energy source for winding and pumping, or acting to suppress dust release, it is more often remembered in mining circles as at least a nuisance, if not a mortal hazard.

Nuisance water

In its more mundane manifestations, as gradual drippers or sustained feeders entering working areas, excessive water is often a nuisance, for it can:

(1) make the work of the miners more laborious and uncomfortable
(2) degrade floor and roof strata, thus hindering haulage and maintenance activities
(3) accelerate the corrosion of mining equipment
(4) necessitate the use of water-resistant machinery and expensive, waterproof explosives, and
(5) add substantially to the weight of the run-of-mine product, making it more difficult and expensive to handle.

All of these problems can be overcome to some degree by means of well-planned and well-managed dewatering and related drainage activities. For the individual miner, the inconvenience caused by wet conditions was eventually assuaged to some degree when bonus payments for 'wet working' were introduced. In terms of the overall financial performance of a mine, the costs of managing large water makes (principally by means of incessant pumping) can make all the difference between a profitable and bankrupt mine. By the mid-19th Century, there were already many collieries which were raising far more water than coal to daylight (Taylor 1858), the record at that time being held by the James Pit at Wylam (Northumberland), which raised 30 tonnes of water for every tonne of coal. This same mine in its flooded state continues to deliver a very large, perennial, ferruginous discharge to the River Tyne (at grid reference NZ 123647), at a point very close to the cottage in which the great mining engineer and railway pioneer George Stephenson was born. Stephenson's famous achievements in steam engineering were based on his early experiences in the James Pit, helping to maintain the substantial steam-driven dewatering pumps (Leifchild 1853). Here is another happy by-product of unwanted ground water ingress to mine workings: the fostering of engineering skills which were to prove key to the furtherance of the industrial revolution. This is a point to which we shall return on several occasions later in this narrative.

Dangerous inrushes

'. . . the watt'ry 'wyest', mair dreedful still, alive oft barries huz belaw:
Oh dear! it myek's yen's blood run chill! May we sic mis'ry niver knaw!
Te be cut off frae kith and kin, the leet o' day te see ne mair
and left frae help and hope shut in, te pine and parish in despair . . .'
(from the Tyneside dialect poem 'The Pitman's Pay'; Wilson 1843)

In the form of violent inrushes to underground workings, water has claimed thousands of lives worldwide, both by drowning and by entrapment of miners in isolated mine voids, where death comes more slowly by asphyxiation or starvation. Few miners survive such inrushes, a notable recent exception being the major Quecreek Mine inrush in Pennsylvania (USA) on 24th July 2002, from which all nine trapped miners were rescued after 77 hours underground. Less happy outcomes have almost always been the norm. Nevertheless, the fatality rate from water inrushes is relatively modest in comparison to other causes of death in underground mines, at around 1.5% of all fatalities (Hyslop *et al.* 1927). This is nevertheless of the same order of magnitude as the fatality rate from explosions of methane and/or coal dust (3%), which are generally accorded far more attention in popular conceptions of the hazards of mining. In fact, the predominant causes of death in mining are far less sensational than either inrushes or explosions and they take their toll day-by-day: falls of ground (50% of all fatalities), mishaps with haulage equipment (25%) and errors in blasting procedures (10%) (Richards 1951).

Table 1 summarizes all major inrushes in Britain from 1648 to 2002. As the table reveals, there are two principal sources of inrushes: flooded old workings and natural bodies of water (aquifers or surface water bodies). Of the two, inrushes from old workings are by far the more common. The risk from old workings was particularly acute prior to 1872, the year in which a statutory requirement to deposit mine plans for future reference was finally introduced. According to Hyslop *et al.* (1927) a further 15 years elapsed before surveying procedure had

Table 1. *Notable mine water inrushes in Britain, 1648–2002*

Date	Mine[a]	Cause of inrush	No. of fatalities	Further information[b]
1 Aug 1648	Two unnamed collieries (Durham)	Workings were rapidly flooded when the River Wear burst its banks	None known	See Archer (1992)
May 1658	Galla Flatt	'Breaking in of water from an old waste'; the victims' bodies were found and buried in 1695	2	Dunn (1848); Galloway (1898); Doyle (1997)
17 Nov 1771	Wylam (Northumberland)	Water flooded down shafts when the River Tyne burst its banks in its greatest-ever recorded flood	None known	See Archer (1992)
17 Nov 1771	North Biddick, Chatershaugh and Low Lambton Collieries (Durham)	Water flooded down shafts when the River Wear burst its banks in its greatest-ever recorded flood	None known	34 pit ponies recorded as drowned. See Galloway (1898, p. 273), and Archer (1992)
08 Sep 1796	Slaty Ford (Northumberland)	No detailed documentation of cause located	6	DMM archive
27 Mar 1807	Discovery Pit, Felling (County Durham)	An advancing bord holed into unsuspected flooded old workings.	3	Hair (1988, p. 72–73)
30 Jun 1809	East Ardsley (Yorkshire)	No detailed documentation of cause located	10	DMM archive
03 May 1815	Heaton Main (Northumberland)	Inrush from old flooded workings of Jesmond Colliery, despite precautionary borings having been made without reaching water	75	Dunn (1848); recently recounted in detail by Doyle (1997)
13 July 1828	Towneley Main Colliery (Durham)	River Derwent (a tributary of the Tyne) burst its banks and flooded the Star Flat Pit	1	14 pit ponies also drowned. See Archer (1992)
3 Dec 1829	Willington (Northumberland)	Gas explosion holed into old workings	4	Hair (1844, p. 16)
7 March 1832	Beamish Colliery (Durham)	'Pit inundated'	2	Galloway (1898, p. 504)
15 Oct 1832	Houghton Colliery (Durham)	Failure of cast-iron tubbing in the main shaft gave rise to a major inrush from the Magnesian Limestone aquifer. Although all the miners escaped, all the ponies in the pit were drowned.	None	Galloway (1898, p. 505)
1833	Workington Lady and Isabella Pits (Cumbria)	Inundated from old workings	4	Galloway (1898, p. 504)
1835	St Helens (Lancashire)	River water burst into mine	17	Galloway (1898, p. 504)
28 Jul 1837	Workington (Cumbria)	Pillar working beneath the sea bed led to cracking of roof strata to sea floor, and a whirlpool in the bay which drowned the mine in seconds	27	Galloway (1904)
4 July 1838	Silkstone (Yorkshire)	Surface water entering an inclined drift ('futterail') during a thunder-storm trapped children against a downward-opening ventilation door.	26	Galloway (1904)
02 May 1839	Kingswood (Somerset)	'Irruption of water'	11	Galloway (1904)
23 Oct 1840	Farnacres, Bensham (Durham)	'Drowned from old workings'	5	DMM archive
'1840–1'	Stronne (Lanarkshire)	Flooded after holing into old workings	4	Galloway (1904)
9 Dec 1842	Fenwick, Belford (Northumberland)	Flooded after holing into old workings	2	Galloway (1904)

Table 1 *(cont.)*

Date	Mine[a]	Cause of inrush	No. of fatalities	Further information[b]
09 Oct 1843	Pasture Hill (Northumberland)	Flooded after holing into old workings	7	DMM archive
14 Feb 1844	Landshipping Colliery, Haverford-west (Glamorgan)	Void migration from shallow workings intercepted bed of River Dunleddy, causing major inrush of river water to mine	40	Dunn (1844); Galloway (1904)
Feb 1845	Haye's Wood (Somerset)	'Irruption of water'	10–11	Galloway (1904)
Dec 1847	Ince Hall Colliery (Lancashire)	River Douglas burst its banks near Wigan and flowed through old workings to the working colliery	Several; number uncertain	Galloway (1904)
10 May 1852	Gwendraeth (Glamorgan)	Quicksand burst into workings from overlying strata	26	DMM archive
11 Jun 1861	Clay Cross No 2 Pit (Derbyshire)	Flooded old workings of No 1 Pit, thought to be 50 yards from working face, were actually only two feet away when the coal gave way	23	See Judge (1994)
10 Feb 1865	Coneygree (Staffordshire)	Advancing mine workings holed into old shaft which was not suspected to pierce the strata at this point	3	See Appendix XVIII in Hyslop *et al.* (1927), in which it is wrongly spelled 'Conygre'
1 Apr 1867	North Levant Tin Mine (Cornwall)	Water entered stope from adjoining old workings of Wheal Maitland	3	See Vivian (1990)
19 Jan 1871	Wheatley Hill (Durham)	Water entered colliery from adjoining old workings of Thornley Colliery	5	DMM archive
24 Jan 1871	Seaham (Durham)	Inaccurate plans (in any case inadequately consulted) in faulted strata resulted in flooded workings being much closer than estimated	2	See Appendix XVIII in Hyslop *et al.* (1927)
30 Mar 1871	Highbridge (Staffordshire)	Sudden large water make from post-Carboniferous strata above unconformity	3	See Appendix XVIII in Hyslop *et al.* (1927)
4 Dec 1875	Penygraig (Glamorgan)	A large fault seen in nearby workings was assumed to separate old and new workings, but the throw of the fault in fact petered out before it reached the Penygraig workings	2	See Appendix XVIII in Hyslop *et al.* (1927)
11 Apr 1877	Tynewydd, Rhondda (Glamorgan)	Mistaken interpretation of old plans in area of confusing faulting	5	See Llewellyn (1992)
10 Mar 1881	Page Bank (Durham)	Flooded when River Wear burst its banks and spilled into shaft	Not known	See Archer (1992)
25 May 1883 29 Oct 1884	Hodbarrow Iron Ore Mine (Cumbria)	Successive inrushes of ground water carrying loose sand from overlying drift deposits. Although these thankfully claimed no lives, they led to major surface subsidence and damage to infrastructure	None	Harris (1970)
03 Jun 1885	Newbottle Margaret Pit (Durham)	Failure of a supposed 200 yard barrier of intact coal, suggesting that the relevant plans were highly inaccurate, even though others of the same period in this area were known to be accurate	14	See Appendix XVIII in Hyslop *et al.* (1927)
20 Dec 1885	Hodbarrow Iron Ore Mine (Cumbria)	Further inrush of ground water carrying loose sand from overlying drift deposits, associated with development of major surface depression inland	None	Harris (1970)

Table 1 *(cont.)*

Date	Mine[a]	Cause of inrush	No. of fatalities	Further information[b]
3 May 1892	Ashton Vale (Somerset)	Advancing mine workings holed into old shaft which was not suspected to pierce the strata at this point	2	Circumstances similar to those at Lofthouse 81 years later. See Appendix XVIII in Hyslop *et al.* (1927)
04 Aug 1892	Ravenslodge (Yorkshire)	Failure of tubbing in upcast shaft allowed sudden inrush of strata water	6	See Command report 6902
14 Jan 1895	Audley (Staffordshire)	Inaccurate plans led to failure of what had been intended as a 80-yard wide barrier separating the mine from old workings of Diglake Colliery	77	See Appendix XVIII in Hyslop *et al.* (1927)
09 Dec 1896	River Level (Glamorgan)	Illegally worked area of coal not shown on plans by miscreants	6	See Command report 8465
26 Mar 1897	Devon Colliery, Furnacebank No. 1 Pit (Clackmannan-shire)	Failure of an access door in an old dam which held water back in abandoned workings	6	See Command report 8637
06 May 1897	East Hetton (Durham)	Inrush from unrecorded old workings	10	DMM archive
18 May 1898	Hodbarrow Iron Ore Mine (Cumbria)	Major inrush of ground water carrying loose sand from overlying drift deposits and sea bed, forming a surface crater in the inter-tidal zone	None	Harris (1970)
4 Sept 1902	Navigation (Gloucester)	Error in current plans led to holing into old workings	4	See Appendix XVIII in Hyslop *et al.* (1927)
16 Nov 1903	Sacriston (Durham)	Sudden failure of a barrier holding back known flooded old workings	2	1 miner survived trapped above water line for 88 hours; see Purdon (1979)
26 Aug 1901	Donibristle (Fife)	Inrush of liquefied peat from the Moss Morran peat bog	8	See Command report 851
27 July 1903	Dudley Wood (Worcestershire)	Advancing mine workings holed into old shaft which was not suspected to pierce the strata at this point	4	See Appendix XVIII in Hyslop *et al.* (1927)
1903	Easington (Durham)	During the sinking of the South Shaft through the Permian Yellow Sands Aquifers by means of ground freezing, an inrush estimated to total about 60 m^3 entered the shaft from an unfrozen pocket	1	See Temple (1998, p. 60–61) and Emery (1992, p. 84)
28 Jan 1908	Roachburn (Cumbria)	Inrush of liquefied peat from overlying bog	3	See Robertson (1997)
15 Feb 1908	Brereton (Staffordshire)	Sudden large water make from post-Carboniferous strata above unconformity	3	See Appendix XVIII in Hyslop *et al.* (1927)
16 Dec 1909	Podmore Hall Minnie Pit (Staffordshire)	Sudden large water make from post-Carboniferous strata above unconformity	1	See Appendix XVIII in Hyslop *et al.* (1927)
24 May 1911	Podmore Hall Minnie Pit (Staffordshire)	Sudden large water make from post-Carboniferous strata above unconformity	1	See Appendix XVIII in Hyslop *et al.* (1927)
23 Dec 1911	Bamfurlong (Lancashire)	Advancing mine workings holed into old shaft which was not suspected to pierce the strata at this point	1	See Appendix XVIII in Hyslop *et al.* (1927)
16 Jun 1913	Car House (Yorkshire)	Unfortunate failure of precautionary boreholes, drilled in accordance with regulations, to detect flooded void	8	See Appendix XVIII in Hyslop *et al.* (1927)
09 Jul 1918	Stanrigg And Arbuckle (Lanarkshire)	Inrush of liquefied peat from surface peat bog	19	See Command report 146

Table 1 *(cont.)*

Date	Mine[a]	Cause of inrush	No. of fatalities	Further information[b]
21 Apr 1923	Shut End (Staffordshire)	Sudden release of water from old goaf through which new roadways had been driven two weeks previously	4	See Appendix XVIII in Hyslop *et al.* (1927)
25 Sep 1923	Redding (Stirlingshire)	Inaccurate plans (in any case inadequately consulted) in faulted strata resulted in flooded workings being much closer than estimated	40	See Command report 2136
10 Mar 1924	Harriseahead (Staffordshire)	Illegally worked area of coal not shown on plans by miscreants	None	See Appendix XVIII in Hyslop *et al.* (1927)
27 Nov 1924	Killan (Glamorgan)	Inaccurate plan falsely implied a wider barrier to flooded old workings than existed	5	See Appendix XII in Hyslop *et al.* (1927)
30 Mar 1925	Scotswood Montague Pit (Northumberland)	Inadequate availability of mine plans led to flooding from documented old workings nearby	38	See Command report 2607
27 Dec 1925	South Hetton	Fault led to unanticipated connection with flooded old workings	None	See Appendix XVIII in Hyslop *et al.* (1927)
07 Sep 1950	Knockshinnock Castle (Ayrshire)	Liquefied peat entered mine from surface bog	13	See Command report no 8180
21 Mar 1973	Lofthouse (Yorkshire)	Longwall panel holed into flooded shaft	7	Last fatal inrush in a British colliery. See Command report 5419 (Calder 1973)
1987 (problems developed over several months)	Sherburn-in-Elmet Gypsum Mine (Yorkshire)	The mine struck a fissure which was in open communication with the Magnesian Limestone Aquifer (Brotherton Formation) at depth below the workings. Despite two attempts at pressure grouting, the battle to save the mine was finally lost	None	Cooper, A. H. British Geological Survey, pers. comm. 2003.
23 Mar 2002	Longannet (Fife)	Sudden failure of a dam which had long held back water in very old workings released some 75 Ml of water in ten minutes	None	Direct cause of closure of this last deep mine in Scotland. Pers. comm. from mine staff.

[a] all are coal mines unless otherwise noted: while every effort has been made to include all inrush records which have come to the author's attention, it must be stressed that records were far more systematically kept for coal mines than for metalliferous/industrial mineral mines and that these categories of mine are almost certainly under-represented in this list. The author will be grateful for any additional records submitted by readers for inclusion in subsequent editions. [b] These are not necessarily the primary references for these incidents. 'Command' reports are official government reports by HM Inspector of Mines, which were usually ordered by the government in the cases of major accidents in mines. 'DMM archive' refers to the archive of mining disasters maintained, on-line and with free access, by the Durham Mining Museum (*www.dmm.org.uk*). This includes entries gathered from old press reports and local history accounts as well as official records

become sufficiently standardized for the deposited plans to become generally reliable. Hence plans dating from before 1887 should be viewed only as 'evidence that old workings existed in the neighbourhood', rather than as indicating the actual position of workings (Hyslop *et al.* 1927).

Significant insights into mine hydrogeology can be gained by reflecting on the circumstances of some of the incidents listed in Table 1. For instance, the inrush at Tynewydd Colliery (Rhondda Valley, South Wales) in 1877 serves to demonstrate just how lowly-permeable Coal Measures shales can be. Although four miners were drowned immediately after an advancing roadway unexpectedly encountered flooded old workings, ten others survived below the water table for a week, in air pockets which were trapped by the rising water table against shale roofs in isolated up-dip workings. Even under substantial excess head from the surrounding water mass, the trapped air did not dissipate into the shales. One of the ten trapped miners was sadly killed at the moment of rescue, when the release of compressed air forced him into the hole dug from above by the rescue brigade, fracturing his skull. The remaining nine men survived, although all suffered from the bends (believed to be the first medically-documented cases of this affliction) following the rapid decompression (Llewellyn 1992). As in the case of Quecreek (Pennsylvania) in 2002, the Tynewydd inrush was an international media sensation of its age, and was quite probably the inspiration for the dramatic inrush entrapment passages which form Part 7 of the classic novel '*Germinal*' by Émile Zola (1885).

Miners gradually devised ever-more effective precautions against devastating inrushes. In fact, the British mining industry has now become so good at mining safely under bodies of water that it has established a world-leading expertise in this field, with an unequalled safety record in workings extending in excess of 10 km offshore (Orchard 1975; Aston and Whittaker 1985). Nevertheless, accidents have continued to occur sporadically, even in onshore coalfields, down to the present day. The most serious inrush in living memory was that at Lofthouse Colliery (West Yorkshire) in 1973, when an advancing longwall face holed into a flooded shaft, taking seven lives (Calder 1973). Most recently of all, the ultimate trigger for closure of the last underground coal mine in Scotland (Longannet) in March 2002 was a major inrush due to failure of an old underground dam (This fortunately failed to claim any lives, as it occurred on a Saturday when few miners were in the pit).

Engineering responses to ground water ingress prior to 1900

Both nuisance water and dangerous inrushes have necessarily received a lot of attention from mining engineers and mining geologists over the centuries. In the following paragraphs, a brief history of some of the methodologies and technologies developed in response to these problems is presented.

The very earliest mines, being little more than scrabblings from conspicuous surface outcrops on hillsides, were largely free from water problems. It was only as mines were developed to greater depths in pursuit of dipping seams and plunging veins that they passed below the local base level of drainage and began to incur the penalty of a heavy water make. The evolution of responses to high water makes followed a four-step progression which can be summarized as follows:

(1) simple bailing of bell pits and other shallow workings using buckets
(2) under-drainage by long adits linking the sole of the workings to the deepest local valley
(3) the pumping of mine water from great depths up to surface watercourses
(4) the use of physical barriers to minimize water ingress to shafts and active workings.

Bailing and its limitations

The most obvious response to the unwanted flooding of any hole with water is to bail the water out using a bucket or similar vessel of larger dimensions. This practice, which is generally termed 'winding water' in mining circles, may be all that is required to enable profitable mining to continue, particularly above the water table in low permeability strata. The very oldest surviving mine workings in Britain (i.e. Neolithic flint mines (Russell 2000), Bronze Age copper mines in North Wales (Jenkins & Lewis 1991; Timberlake & Jenkins 2001) and the Roman gold mine at Dolaucothi in South Wales (Burnham 1997)) are all above the local water table and would never have required anything more than bailing to secure access to working faces. The same is true of the vast majority of pre-1600 coal mine workings, which were typically in the form of modest bell-pits well above the local base-level of drainage (Levine & Wrightson 1991). Even after the progression of coal mines below the water table, shaft haulage of water to surface using kibbles (i.e. large buckets used in shaft sinking and maintenance) continued to play a significant role in mine dewatering in many places. Eye witness accounts record this practice at certain Tyneside pits in 1724, 1740 and 1848 (Clerk 1740; Dunn 1848; Atkinson 1966). Throughout the mid-19th Century, winding water was common practice in several Midlands coalfields, with the simple kibble (or 'bowk' as they were locally called) often being replaced by purpose-designed side-discharging tanks running on cage-guides (Knipe per. comm. 2003). Even in modern times, pumping is still occasionally augmented under exceptional circumstances by winding water (Sinclair 1958) using shaft hoisting equipment. For instance, in February 1921 East Pool tin mine (Camborne, Cornwall) closed, and by a terrible coincidence its main pumping shaft collapsed five months later. After about two years, the East Pool workings had flooded up to the level of the lowest decant route into the adjoining workings of South Crofty mine. In April 1923, virtually the entire former East Pool water-make began to flow unhindered into South Crofty, and in the struggle to cope with the sudden doubling of the latter mine's water make, the winding engines were used for water hoisting for seven months, until sufficient extra pumping capacity could be installed (Buckley 1997, p. 116–118).

Clearly there are severe practical limitations on the use of bailing as the principal means of dewatering a mine which is accessible only by shafts. In *The Compleat Collier* of 1708, manual bailing is mentioned as the first option for coal mine drainage, with horse gins being used for bailing from shafts deeper than about 50 m ('J.C.' 1708, p. 20). In a study of the development of the Wet Earth Colliery (Lancashire) during the 18th and 19th centuries, Banks and Schofield (1968) used *prima facie* reasoning to quantify the limiting water make beyond which bailing via a shaft becomes impractical if a colliery is to continue producing coal without frequent interruptions. The figures they obtained are based on shaft and kibble dimensions which were typical for underground mines throughout 19th Century Britain, and therefore are likely of generic applicability. By consideration of the motive power available from horse-powered whim gins and a kibble capacity on the order of 600 gallons, for the 48 m shaft at Wet Earth Colliery they obtain a maximum manageable inflow rate of about 4.5 ls^{-1}. For deeper collieries, other studies cited by Banks and Schofield (1968) suggest that the limiting inflow rate beyond which bailing will be insufficient is around 2 to 3 ls^{-1}. For inflows greater than this, mines will either have been pumped or else abandoned.

In some parts of Britain the progression in ground water control technology was directly from bailing to pumping. This was particularly so in areas such as the Grassington Moor lead orefield (North Yorkshire), where the topography was not suited to the development of adit drainage (Morrison 1998). However, in the majority of mining districts, the development of efficient pumping technology lagged some years behind the desire to delve deeper (e.g. 'J.C.' 1708), and adit drainage succeeded simple bailing as the preferred means of mine dewatering.

Drainage adits

Adits are simply long tunnels which are driven from some hillside to intersect wet underground workings for the purpose of under-draining them by free gravity flow to the portal of the tunnel. Most adits give the appearance of being horizontal in disposition, but careful surveying generally reveals them to slope gently towards their portals (1-in-500 is a common grade), as this favours free drainage and the avoidance of inconvenient ponded areas.

Adit technology has been around for a very long time. For instance, Buckley (2000) has noted the existence of an apparent reference to the excavation of drainage adits in the Book of Job. In this Old Testament biblical text, a succinct summary of metalliferous mining includes the following lines:

> '. . . Men dig the shafts of mines . . . Men dig the hardest rocks,
> dig mountains away at their base . . . As they tunnel through the rocks
> they discover precious stones. They dig to the sources of rivers
> and bring to light what is hidden . . .'
> (Book of Job, Chapter 28, verses 4, 9 and 11, as in the United Bible Societies' Translation of 1976)

Although the dating of specific texts in the Book of Job is a significant challenge for Old Testament scholars, it is safe to say that the above quotation refers to mining practices which were taking place more than 2500 years before present (Anderson pers. comm. 2002). Archaeological evidence has revealed that adit drainage technology was well-known in the Roman Empire. Davies (1935) documents Roman drainage adits in gold mines of Spain, Greece and Slovakia, some of which reached lengths as great as 2 km.

Metal mine drainage adits prior to 1600

At none of the known sites of prehistoric metalliferous mining in Britain have workings been found to have extended deep enough for adit technology to be necessary. Only at one suspected Roman lead mining site at Greenhow Hill (North Yorkshire) is there a possibility that a surviving gallery (the Jackass Level) at one time served in part as a drainage adit, though if this was indeed the case it has long-since been dewatered as the water table was lowered by adjoining drainage adits which were driven in the 19th century. Despite their known familiarity with adit technology, therefore, it remains a moot point whether, during their 400-year occupation of the island, the Romans dewatered their metalliferous mines in Britain by this means. According to documentary evidence recently reviewed by Buckley (2000) it is not until the late 13th century that clear evidence emerges for the installation and maintenance of drainage adits in metalliferous mines. A document dating from 1308 provides what is possibly the earliest recorded instance of roof-fall clearance works in a drainage adit. These works were undertaken to facilitate the re-opening in 1292 of silver mines on the eastern bank of the River Tamar in Devon. The work specified included 'clearing of adits and workings of dead work (rubble) . . . [and] penetrating a blockage of rock, in length 22½ fathoms, which had been stopping the water in the highest part of the mine of Furshill, where it touched the minerals being worked' (Buckley 2000, p. 26). Another very early example comes from the rather modest lead mining district of Rossendale (Lancashire) in relation to which financial accounts covering the year 1304–1305 include an entry for payment 'to the miners for making a certain trench underground to draw the water off from other trenches' (see Raistrick & Jennings 1965, p. 71). In the more substantial lead mining district of Weardale (County Durham), the driving of a 'watergate' (a north country term for a drainage adit) at a site called

Balkden is recorded in a financial account dated 1426 (Raistrick & Jennnings 1965, p. 71). Sporadic further references to the use of drainage adits in the metal-mining districts of Devon and Cornwall continue throughout the 14th and 15th Centuries, mirroring the development of metal-mining technology elsewhere in Europe up to the mid-16th Century state-of-the-art as described in Agricola's *De Re Metallica* of 1556 (Hoover & Hoover 1950).

Coal mine drainage adits prior to 1600

Coal was used to a limited extent in ancient times, but archaeological evidence has long indicated that its early use was largely restricted to metallurgical applications (Taylor 1858; Galloway 1898). For instance, while it has been found in association with metal-working remains in the Roman Camps along Hadrian's Wall (Northumberland), it has long been noted that conspicuous exposures of coal in close proximity to several of the camps show no evidence of having been worked on a scale consistent with domestic use during Roman times (Taylor 1858). Given the apparent indifference of the Romans in Britain to the possibilities of coal as a major fuel source, it is not surprising that no firm evidence exists for dewatering adits of Roman origin in Britain. Ancient mine roadways with a disposition which suggests they may once have served as drainage adits are occasionally unearthed during opencast mining. Some of these features have dimensions similar to those of known Roman adits in Mediterranean countries, which has prompted speculation that they may indeed be of Roman origin. However, no firm dating evidence (from timbers etc) has ever been found to substantiate such conjectures. On balance it seems unlikely that the Romans experienced such severe shortages of firewood that they needed to mine coal far underground. Such ancient mine roadways are thus more likely to be of mediaeval origin.

Little changed in the scale of exploitation of coal, and hence in associated dewatering needs, in the first millennium following the departure of the Romans. For instance, in the third decade of the 8th Century, in writing the first history of the English-speaking people, the monk Bede (746) noted the presence of 'rich veins of metal – copper, iron, lead and silver' in Britain, but had only this to say about the coal which is so abundant in the vicinity of the Tyneside monastery where he spent his entire life: 'This is a glossy black stone which burns when placed in the fire; when kindled it drives away snakes' (The fact that coal was noted as burning 'when placed in the fire' indicates that it was not the normal domestic fuel of the day, which must still have been wood in that period). Indeed, it is not until January 26th 1357–1358 that coal mining had advanced to the extent that problems of coal mine drainage could make their first appearance in the documented history of Britain, in the form of a complaint from the Prior of Tynemouth to the King of England to the effect that 'the men of Newcastle were digging in his moor of Elswick, and endeavouring to demolish the drain (*seweram*) from his mine in Elswick Moor, which was the chief form of sustenance of himself and his house' (Galloway 1898, p. 42). Although Taylor (1858) suggests that pipe rolls dated 19th February 1367 can be interpreted as implying the driving of drainage adits at coal mines in the vicinity of Birtley and Winlaton (northern County Durham), the earliest unequivocal records of the deliberate construction of coal mine drainage adits (as opposed to their destruction, as described in the 1357–1358 Elswick case) are found in the 15th Century financial records of Finchale Priory, a Benedictine monastery in the Wear Valley some five kilometres north of Durham City. In 1428, the monks of Finchale drove a 'water-gate' at nearby Coxhoe, a venture which proved reasonably successful in comparison with further drainage adit projects in the Durham area which they undertook subsequently at Softley (1433–1434) and Baxtandfordwood (1442–1443). In Scotland, records dating from 1531 document monks of Newbattle Abbey planning the construction of coal mine drainage adits to carry water down to the sea in the vicinity of Prestongrange (Midlothian), a few kilometres east of Edinburgh (McKechnie & MacGregor 1958) (Interestingly, during 2002 the Prestongrange sea-adits became the focus of renewed attention, during the investigation of mine water impacts on transport infrastructure in the area).

Mine drainage adits after the advent of gunpowder

It is essential to note that all drainage adits driven in Britain before the mid-17th Century, in both metal- and coal-mines, were excavated without the aid of explosives (Ford & Rieuwerts 2000, p. 24). This is the principal reason why, as Raistrick and Jennings (1965, p. 71) have noted, 'adits for mine drainage did not come in to general use until the seventeenth and eighteenth centuries'. It was only after the widespread adoption of gunpowder for blasting in the decades following 1630 that drainage adits commonly began to extend over distances of more than one or two kilometres. Table 2 summarizes some of the more significant drainage adits constructed in Britain between 1600 and 1900.

It is immediately evident from Table 2 that Derbyshire was Britain's pioneering region in the development of explosives-driven drainage adits (Ford & Rieuwerts 2000), with many of the major drainage adits in that County dating from the 17th Century. The principal reason why gunpowder-driven adits were developed in Derbyshire much earlier than elsewhere is quite simple: the majority of lead ore deposits in the Derbyshire orefield are

Table 2. *A summary of some of the more importanta drainage adits driven in Britain between 1600 and 1900*

Year driveage commenced/ first noted	Name of adit	Location	Type of mine drained by adit	Comments	Source of information
1617	Black Burn Watergate	Durham	Coal	Driven to underdrain the world's first industrial-scale collieries on Whickham Fell, Gateshead. Still flowing in 2002 despite considerable under-drainage by pumping at Kibblesworth Colliery nearby	Levine & Wrightson (1991); Clavering (1994)
1627	Weet Sough	Derbyshire	Lead	Located at Winster; the earliest known extant drainage adit in Derbyshire	Ford & Rieuwerts (2000)
1632	Dovegang Sough	Derbyshire	Lead	Driven from Cromford Hill by Sir Cornelius Vermuyden; widely (if erroneously) quoted as the first drainage adit in England, but was almost certainly the earliest drainage adit to extend for more than a few hundred metres	Ford & Rieuwerts (2000)
1653	Aspull (Haigh) Sough	Lancashire	Coal	Originally driven by Sir Roger Bradshaigh (1025 m) from 1653 to 1670; subsequently extended a further 1575m by about 1856. Continues to be a source of pollution to the present day	Unpublished Coal Authority records
1654	Tideslow Sough	Derbyshire	Lead	Had reached a length of 800 m by the winter of 1685	Ford & Rieuwerts (2000)
1657	Longe Sough	Derbyshire	Lead	Also known as Cromford Sough; also extends several hundred metres	Ford & Rieuwerts (2000)
1657	Bates Sough	Derbyshire	Lead	The third major 17th Century sough in the Cromford area	Ford & Rieuwerts (2000)
1687	Winster Sough	Derbyshire	Lead	Drains the Portaway Pipe deposit	Ford & Rieuwerts (2000)
@ 1670	Delaval Drift	Northumberland	Coal	Draining the pits of West Kenton, Newbiggin and Whorlton down to the Tyne at Benwell. The portal of this drift (no longer flowing due to subsequent under-mining and sustained pumping at Kibblesworth, Gateshead) was found and preserved in the 1980s during redevelopment of the west end of Newcastle (see Fig. 1a)	Galloway (1898, p. 161)
1693	Hannage Sough	Derbyshire	Lead	Drains the mines north of Wirksworth to its portal at Willowbath Mill	Ford & Rieuwerts (2000)
1700	Stanton Sough	Derbyshire	Lead	Noted as being 'a mile in length by 1700'	Ford & Rieuwerts (2000)
1711	Pool Adit	Cornwall	Copper	Thought to be the first major adit in Cornwall to be driven entirely using gunpowder blasting technology. Later largely under-drained by the Dolcoath Deep Adit (see below)	Buckley (2000)
1723	Apes Tor Sough	Staffordshire	Copper	The first of five major levels driven to drain the major Cu-Pb mine complex of Ecton Hill, North Staffordshire. Total length approximately 340 m	Robey & Porter (1972)
1729	Tanfield Watergate	Durham	Coal	An adit running for several kilometres through the Beckley and Tanfield collieries, for which a wayleave of £2000 was paid, and which contributed to under-draining the Stanley area of Co. Durham to depths in excess of 120 m	Galloway (1898, p. 250)
1737	Clayton Level	Staffordshire	Copper and lead	The second of five major drainage adits to be driven into Ecton Hill, in this case to under-drain the Clayton Pipe Vein. Total driveage approximately 0.6 km	Robey & Porter (1972)
1742	Great County Adit	Cornwall	Copper and Tin	The pre-eminent drainage adit amongst all the metalliferous mining fields of the UK, eventually totalling more than 55 km of driveage, and remaining a continued source of polluted drainage to this day, with an average flow of around 0.4 m^3s^{-1}; see text for further details	Buckley (2000)
1750	Fordell Day Level	Fife	Coal	Originally driven from portal near Fordell Castle (by Inverkeithing) 3.2 km to Drumcooper Pit (reached about 1800); by 1850, further extended by 2.3 km to William Pit. Major source of mine water pollution at the present day	Unpublished Coal Authority records

@ 1751	Tailrace Level	Durham	Lead	This level was apparently initiated at the commencement of mining in the Scarsike Veins of Rookhope, Weardale. It had certainly attained a length of 1.5 km by the early 19th Century, when a 1 km extension of the level to Grove Rake Mine was initiated. The level is currently a major source of polluted drainage to the Rookhope Burn	Fairbairn (1996); Johnson & Younger (2000)
1759	Chaddock Level	Lancashire	Coal	Underground extension of the Bridgewater Canal; a continued source of polluted mine drainage. See text for further details	Mullineux (1988)
@ 1760	Dolcoath Deep Adit	Cornwall	Copper/tin	Driven from Roscroggan on the Red River, through Roskear to Dolcoath; this adit was the last drainage adit in Cornwall to form part of a working mine (South Crofty, closed 1998) and remains a source of river pollution	See Younger (1998); Buckley (2000); Adams & Younger (2002);
1765	Elginhaugh Daylevel	Midlothian	Coal	Portal on the River North Esk, drains ancient workings (some Mediaeval, associated with Newbattle Abbey) in the Whitehill Rough Seam. Estimated 1.6 km length into area of major workings	Unpublished Coal Authority records
1766	Hill Carr Sough	Derbyshire	Lead	Took more than 20 years to under-drain main target vein; so much water was released that the level was later used for barge haulage of ore	Ford & Rieuwerts (2000)
1770	Kitty's Drift	Northumberland	Coal	More than 3 km in length, this adit provided drainage and haulage of coals to the river for a number of large collieries to the west of Newcastle city	Galloway (1898, p. 268)
1772	Meerbrook Sough	Derbyshire	Lead	Driven to under-drain mines in the Cromford and Wirksworth areas, it was 3 km long by 1805, and was later driven further between 1842 and 1882. Continues to yield a major flow of good quality ground water	Ford & Rieuwerts (2000, p. 53)
1774	Ecton Deep Level	Staffordshire	Copper	Driven approximately 400 m from the banks of the River Manifold, this adit under-drained the earlier Apes Tor Sough to open up more workable ground in the Ecton Pipe Vein	Robey & Porter (1972)
1776	Nent Force Level	Cumberland	Lead and Zinc	Underdrains the mines of Nenthead and the Nent Valley down to a portal adjacent to Alston. By 1842, some 8 km had been driven, achieving some 220 m of drawdown at its greatest extension. The Nent Force Level remains today a major element in the hydrology of the area (mean flow: 0.02 m^3s^{-1}), and a significant source of Zn pollution to the Rivers Nent and South Tyne	See Nuttall & Younger (1999); also Wilkinson (2001)
1782	Gillfield Level	North Yorkshire	Lead	The first of three major drainage adits which contribute to the drainage of the Greenhow Hill lead mining field. Along its 1.9 km driveage it intersects three veins (it is driven on lode in the Coldstone Sun Vein) and continues to yield a significant flow of good quality water to this day	Dunham and Wilson (1985); Everett (1997); Gill (1998)
@ 1800	Golynos Watercourse	Torfaen (South Wales)	Coal and ironstone	Originally an ironstone drift mine in the Bottom Vein Minestone of the Abersychan district, it was extended over the years to its current 1km length to provide drainage to extensive coal workings in the Garw Seam	Walker, P., Big Pit National Mining Museum of Wales, pers. comm. 2003.
1818	Halkyn Deep Level	Clwyd (N Wales)	Lead	Also known as the 'Old Drainage', this adit was driven from the Nant-y-Fflint at some 55 m above sea-level, finally totalling more than 8 km in length prior to losing its functionality when it was under-drained by the even deeper Milwr Tunnel in the early 20th Century (see final entry in this Table)	Williams (1997)
1825	Perseverance Level	North Yorkshire	Lead	The second of three major drainage adits to under-drain Greenhow Hill. Totalling more than 800 m driveage, this adit yields a substantial flow of ferruginous water to this day	Dunham and Wilson (1985); Everett (1997); Gill (1998)

Table 2 *(cont.)*

Year driveage commenced/ first noted	Name of adit	Location	Type of mine drained by adit	Comments	Source of information
1825	Eagle Level	North Yorkshire	Lead	The third of the major adits under-draining Greenhow Hill. Totalling 2.4 km of driveage by completion in 1850, Eagle Level failed to open up significant new ore reserves, and also failed to significantly draw the water table down near its forehead, despite achieving a water make of some 0.06 m^3s^{-1} (which was until recently used for public supply by Yorkshire Water)	Dunham & Wilson (1985); Everett (1997); Gill (1998); Younger (1998).
1853	Lucy Tongue Level	Cumberland	Lead	Driven to under-drain (and later to receive water pumped from deeper workings in) the great Greenside Mine, Glenridding. 1.7 km in total length. Remained in constant use until the mine closed in 1962	Shaw (1970)
1855	Blackett Level	Northumberland	Lead	Driving continued until 1912, reaching a total length of some 7 km. Substantially under-drains the major lead mining field of East Allendale and Allenheads, sustaining a permanent drawdown on the order of 180m, with a mean flow of around 0.1 m^3s^{-1}. See Figure 1b.	Raistrick & Jennings (1965, p. 222–223); Dunham (1990, p. 161–165).
1864	Sir Francis Level	North Yorkshire	Lead	One of the few long adits in the Swaledale mining district, driving continued until 1877, totalling 1.4 km. The adit allowed gravitational and pumped under-drainage of the Gunnerside Gill mines	Raistrick (1975); Gill (2001).
1870	Bullhouse Water Drift	South Yorkshire	Coal	600 m long 1:300 grade drainage adit with portal on the banks of the River Don, draining a large volume of workings in the Halifax Hard Seam. Now the site of a major Coal Authority mine water treatment system	Unpublished Coal Authority records
pre-1880	Old Meadows Waterloose	West Yorkshire	Coal	1:150 grade purpose-driven drainage adit extending 343 m from the banks of the River Irwell into the Lower Mountain seam. Now the site of a major Coal Authority mine water treatment system	Unpublished Coal Authority records
1880	River Arch Level	Torfaen (South Wales)	Coal and Ironstone	Approximately 1 km in length, incorporating a culverted section of a local river (the Afon Lwyd) in the vicinity of Blaenafon, and connected into several pre-existing mine entries, including the Woods Level and the Forge Level. Drains coal and ironstone workings to the N, W and E of the Big Pit (Pwll Mawr), the National Mining Museum of Wales (Blaenafon), for which it also provides secondary egress	Walker, P., Big Pit National Mining Museum of Wales, pers. comm. 2003.
1897	Milwr Tunnel	Flintshire (N Wales)	Lead and Zinc	A major adit with portal invert just above sea-level, providing under-drainage for the limestone-hosted Pb-Zn vein deposits of Halkyn Mountain. It under-drained and wholly superseded the earlier Halkyn Deep Level (driveage commenced 1818; see entry above). The mines drained by the adit were worked until 1987; to this day, the Milwr Tunnel sustains an average flow of some 1.2 m^3s^{-1} (with peak flows up to 4.4 m^3s^{-1}), making it the most prolifically yielding mine drainage adit in Britain (and one of the most prolific in the world), reflecting the karstified nature of the limestone country rock of the Halkyn Mountain Orefield.	Ebbs (1993, 2000); Lynch, R., MCG Consultancy Services Ltd, pers. comm. 2003.

Whether an adit is deemed sufficiently ‘important’ to include here is judged on the grounds of its antiquity, scale, length, or continued importance as a drainage route at the present day.

hosted within permeable, locally karstified Dinantian limestone aquifers (e.g. Ford & Rieuwerts 2000), whereas such prolific aquifers are only sporadically in contact with similar ore bodies in the North Pennines (Dunham & Wilson 1985; Dunham 1990; Johnson & Younger 2002) and are utterly absent from the orefields of Cornwall and Wales. Fortunately, the deeply-incised landscape of the Derbyshire lead orefield lent itself perfectly to the installation of relatively short, deep drainage adits. By contrast, 'in Yorkshire the shape of the ground called for much longer soughs, and only a few were ever driven at great capital cost, and these mainly towards the end of the eighteenth and in the early nineteenth century' (Raistrick & Jennings 1965 p. 132). The sheer volumes of water encountered in the Derbyshire mines also led to the development of many adits dedicated solely to drainage (the term 'sough' denoting a drainage adit only, and never referring to a multiple-purpose adit). Again in contrast, the major adits in the North Pennine orefields were typically multiple-purpose, serving as exploration levels and horse haulage levels as well as drainage galleries (Dunham & Wilson 1985; Dunham 1990; Raistrick & Jennings 1965). Being the first district to embrace gunpowder for adit driveage, the Derbyshire mining engineers acquired skills and experiences which equipped them to profit from transferring their adit-driving techniques to the coalfields (e.g. Aspull Sough in Lancashire and the Delaval Drift near Newcastle; Table 2). By the middle of the 18th Century, such techniques were apparently commonplace throughout the British coalfields, as Clerk (1740, p. 19) noted in relation to the development of drainage adits in the collieries of central Scotland: '... now all who know the true method of running mines have fallen into the German manner of blowing up the hard strata in their way with gunpowder ...'. Notwithstanding the widespread adoption of powder blasting techniques, Clerk (1740) was of the opinion that drainage adits much longer than about 900m were unlikely to be economic to drive or maintain. As Table 2 reveals, this analysis was not borne out by later practice, with coal mine drainage adits in Clerk's native Scotland exceeding 5 km in length within the century following his declaration.

Gunpowder-based adit driving was introduced to Cornwall from the Mendip lead mines in 1689 (Buckley 2000). By 1711 the stage was set for the perfection of the technique in the hard-rock mining terrain in the vicinity of Camborne (e.g. Pryce 1778; Buckley 2000) with the inauguration of the Pool Adit (Table 2). By the start of the 19th Century the mining engineers of Cornwall and Devon had so honed their skills that they came to be in demand even in Derbyshire, the erstwhile heartland of British adit-driving technology. Thus we find the famous Cornish engineer Richard Trevithick engaged in improving the dewatering operations associated with Hill Carr Sough (Table 2) in 1801 (Ford & Rieuwerts 2000, p. 54), and the great engineer of the Devon copper mines John Taylor (Burt 1977) deeply involved in mine drainage and development works at Alport, Derbyshire in the 1830s and 40s (Ford & Rieuwerts 2000, p. 54–55).

Many of the adits listed in Table 2 continue to flow to the present day (Fig. 1), representing permanent changes in the ground water regimes in their host catchments (e.g. Banks *et al.* 1996; Younger 1998). While some of these adits represent sustained, point sources of water pollution in their host catchments (e.g. Younger 1998), others are of such good quality that they have been harnessed for public water supply use (Banks *et al.* 1996).

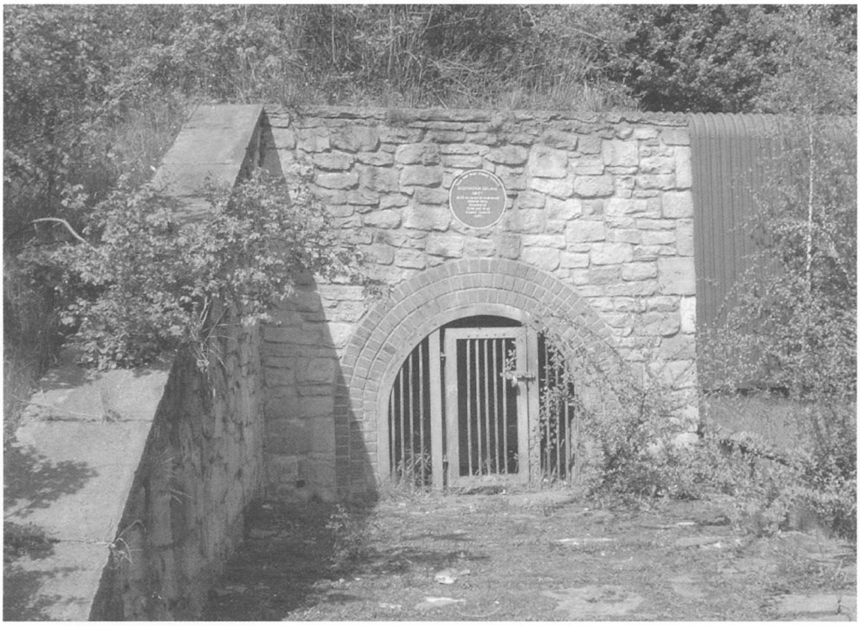
Even where the flow of such adits diminished or ceased altogether after they were subsequently under-drained by later, deeper workings, they can take out a new lease on life after the deeper dewatering eventually ceases. Two recent examples of this phenomenon are as follows:

(1) the Tunnel Pit, near Standish in southern Lancashire, was served by a 1 km coal mine drainage and barge-haulage adit, which was originally in direct communication with the Wigan-Liverpool Canal. Before the end of the 19th Century the Tunnel Pit had been under-drained by pumping in nearby shafts, and it was therefore decommissioned and its portal sealed and buried. Mining in the vicinity finally ceased in the 1960s and 30 years later water began to flow once more from the then-forgotten, buried tail reaches of the Tunnel Pit. To prevent excessive head build-up (with the risk of a sudden outbreak) and to drain the water to a nearby reed-bed which affords some treatment of the water, a number of relief wells have been recently drilled behind the old Tunnel Pit portal plug (Whitworth 2002).

(2) the Tailrace Level (Table 2) is a major drainage adit in the heart of the North Pennine lead orefield. Throughout living memory, the Tailrace Level had discharged an average of 0.86 Mld^{-1} of fairly good quality water. Following the 1999 closure of the last mine in the area, which lies 2.5 km upstream of the Tailrace Level portal, the flow rate of the Level increased by more than 1 Mld^{-1}, and the quality of the water deteriorated such that it carried tens of milligrammes per litre of each of the contaminant metals Fe, Mn and Zn (Johnson & Younger 2002).

To fully appreciate the scale of disruption of natural hydrogeological conditions wrought by the more extensive adit systems, it is worthwhile considering in

(a)



(b)

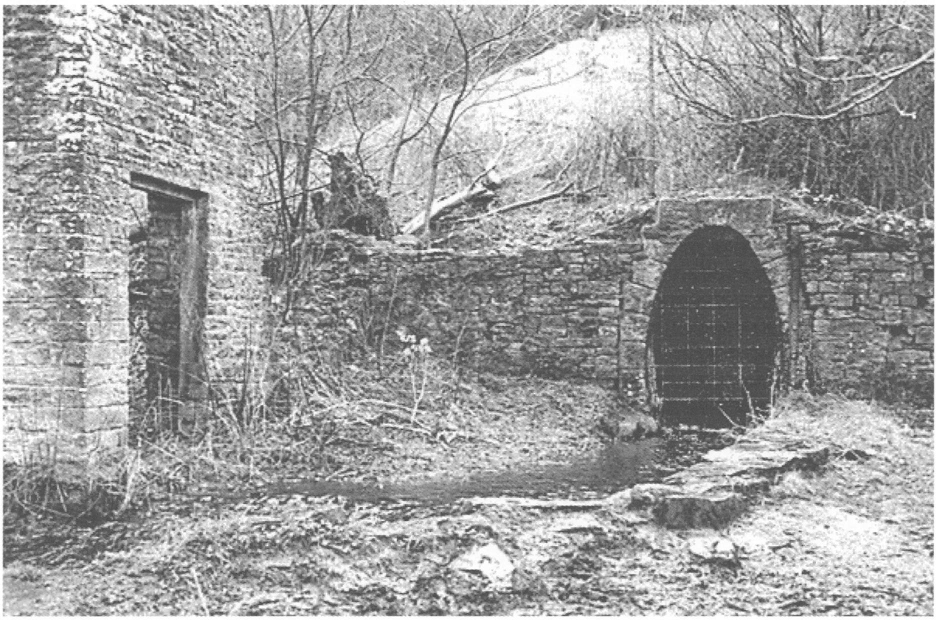


Fig. 1. Two examples of long-established drainage adits remaining long after the closures of their respective mines. (**a**) A 17th Century coal mine drainage adit: the portal of the Delaval Drift on Scotswood Road, Newcastle Upon Tyne, which was driven from around 1670 onwards to under-drain extensive workings to the west and north of the city of Newcastle (see Table 2). (Photo: P L Younger). (**b**) A 19th Century lead mine drainage adit: the Blackett Level, Allendale Town, Northumberland in 1997 (see Table 2). (Photo: A Doyle).

a little more detail two of largest drainage adits ever constructed in Britain: the Great County Adit of Cornwall (which drained the tin and copper mines of western Cornwall) and the Chaddock Level, which drained the coal mines of the Worsley area (Lancashire) into the Bridgewater Canal.

The driving of the Great County Adit was initiated in the Carnon Valley of western Cornwall in 1742 (Buckley 2000), with the initial aim of achieving a total driveage of about 4.2 km (2.5 miles) to drain the mines of Poldice all the way to their westernmost extremity. By 1760, the adit had already achieved this aim and was soon extended by means of various branch-levels to underdrain adjoining mines. Extensions to the County Adit system continued to be added until around 1870. By that year the scale of the entire County Adit system was truly staggering (Buckley 2000). Although no part of the Great County Adit was ever to lie at any greater linear distance than 9.2 km from the portal, the ramifications of the adit system meant that far greater distances than this could be travelled by ground water as it made its way from the outermost drained workings to daylight in the Carnon Valley. Overall, the full dendritic network of adit passageways totalled more than 55 km, and under-drained an area in excess of 33 km^2. Although the mines under-drained by the Great County Adit had mostly been abandoned by 1900 (Buckley 2000) it remains a major element of the ground water – surface water interactions of west Cornwall to this day, for it continues to intercept between 40% and 60% of the total effective precipitation falling on the overlying ground surface (Younger 1998).

The name 'Bridgewater Canal' is truly applicable only to an artificial surface waterway which links Manchester with Runcorn in Cheshire (Mullineux 1988). However, this canal came to be so intimately and directly linked with a large system of underground coal workings in the vicinity of Worsley in Lancashire that the name 'Bridgewater Canal' is now also loosely used to refer also to Britain's greatest-ever combined drainage adit and subsurface coal barge haulage system (Whitworth 2002). Extension of the Bridgewater Canal into the subsurface commenced in 1759, in part to supercede a number of more modest pre-existing drainage adits in the vicinity. The subsurface section of the Bridgewater Canal is called the Chaddock Level (Mullineux 1988), and this eventually extended more than 6 km from its portal at Worsley, linking the extensive underground workings of three collieries (Chaddock, Queen Anne and Henfold), all of which were thus able to ship their coals directly from the subsurface into canal barges, which were as long as 14 m by 1.37 m wide (Whitworth 2002). At the height of its extension around the beginning of the 19th Century, the Chaddock Level comprised more than 86 km of underground canal-ways capable of accommodating barges developed on four distinct levels with major systems of underground locks and self-acting haulage (Galloway 1898, p. 330) by means of which the weight of a full barge was used to pull an empty barge up to a higher level. The Chaddock Level remained in dual usage until 1887, when rail haulage of coal at surface was introduced to the district (Mullineux 1988). However, Chaddock Level did retain a useful drainage function until the closure of the nearby Mosley Common Colliery in 1968. To this day, the perennial discharge of ferruginous water from the Chaddock Level remains an important source of discoloration in the Bridgewater Canal.

Mine water pumping

The full story of the evolution of water-lifting technology has been documented elsewhere (e.g. Hill 1984; Walker 1995) and a reiteration of that documentation is beyond the scope of this paper. Only a partial summary, focused on the exigencies of the mining sector, will be given here, with an emphasis on technologies employed before 1881, when underground electrification began to be introduced in British collieries (Hill 1991).

In one sense, the pumping of water from mine workings is a mere sub-plot of the wider history of water-lifting technology. The earliest pumps in the world were almost certainly developed for purposes of irrigation (Hill 1984), and many of the devices invented for that purpose formed the basis for the technology used to this day in mines worldwide. For instance, a clear reflection of the Archimedean Screw of the ancient Mediterranean cultures (Hill 1984) is to be found in the robust Mono™ pumps which have been the technology of choice for pumping the most turbid of coal mine waters since the 1950s (Sinclair 1958, p. 98). However, certain types of pump which are abundant in other contexts, (such as the simple 'swape' or *shaduf* (Hill 1984), in which a bag of water is raised on a long pole passing over a fulcrum beyond which the short end of the pole is weighted), are never mentioned as being applied in the context of mining, no doubt due to the shortage of space for swinging the loaded pole in a cramped mine gallery. Up to about 1700, it is probably fair to say that mine water pumping technology was a mere sub-set of that used elsewhere. However, between 1700 and 1900, the development of automated pumping in the mining industry far outpaced that in any other industry, so that it is also fair to say that mining provided the technical wherewithal for the development of the world's first large-scale public water supply systems based on the pumping of ground water.

Classical references to mine water pumping principally relate to Roman mines in Mediterranean lands. It is clear from both contemporaneous accounts and from archaeological finds (especially in Spain; Davies 1935; Flores Caballero 1981) that the Romans employed a wide range of technologies, including simple force pumps, a rotating bucket device known as the *Tympanum*, Archimedean screws, and large-diameter, manually- or treadmill-operated bucket-wheels known as *noria* (Hill 1984). Just as the evidence for Roman mining in Britain is scant, so we are as yet bereft of direct evidence that these technologies were used in mines here.

At a later stage of historical development, the well-known 16th Century German mining engineering treatise *De Re Metallica* by Georgius Agricola (Hoover & Hoover 1950) includes the world's earliest descriptions of various adaptations of the *noria* and newer pumping technologies such as the rag-and-chain pump which we know for certain were in use in Britain around the same time. Probably the earliest reference to an automated water-lifting device in use in a British mine comes from the Abbey of Finchale (County Durham) whence expense records for the year 1486–1487 (i.e. 70 years before the first appearance of Agricola's *De Re Metallica*) register the expenditure of £9 25s. 6d. '*de le pompe*', relating to the construction of a new pump, apparently driven by a horse gin, for the dewatering of a colliery at a site named Moorhouseclose. Annual expenditures recorded in the following years attest to the ongoing use and maintenance of this pump (Galloway 1898, p. 71). That this was not an isolated development is suggested by another surviving expense record dating from 1492, which registers a payment for 'two great chains' to be employed in drawing water and coals from a mine in the manor of Whickham, some 12 km north of Finchale (Levine & Wrightson 1991, p. 13). While this reference to the dual use of the chains for drawing coals suggests a large-scale bailing operation, we will never know for sure what form the pumps at Moorhouseclose and Whickham took. Bailing operations and tantalisingly-undescribed pumps are mentioned a century later in Cornwall (in Richard Carew's Survey of Cornwall in the 1580s, as summarized by Buckley 2000, p. 28). However, by the 1600s it is at last evident that British mines in general, and the collieries of NE England in particular, were being pumped by rag-and-chain pumps (Clavering 1994). 'Chain engines', as rag-and-chain pumps were then colloquially known, 'drew water up a standing wooden pipe by means of discs mounted on a continuous chain' (Clavering 1994). *Prima facie* reasoning based on the weight of the chains and the water, the strength of chains and the frictional resistance in the wooden riser pipe, suggests that each individual chain pump was incapable of lifting water more than about 30 m (Clavering 1994). Multiple-stage lifts were therefore necessary if water needed to be lifted more than 30 m.

Water powered mine pumps

Although horse gins were used to drive these chain engines in some places and wind power was also considered as an option (Sinclair 1672; 'J.C.' 1708; Clerk 1740), waterwheels were the preferred power source wherever this was feasible. Indeed waterwheels driving mine pumps became so widespread in the coalfields that they came to be denominated by a specific term: 'coalmills' (Clavering 1994). In the 17th Century, colliery owners found coalmills so much more cost-effective than horse gins that they went to considerable lengths to divert water around hillsides for many kilometres to ensure a sufficient supply for their purposes. One such water diversion system was The Trench, a still-visible canal which led water for some 3.5 km from a small dam on a tributary of the Black Burn (NZ 223598) to a three-stage coalmill at Ravensworth Close (Co Durham) (NZ 238594). An unusually detailed contemporaneous account of this system is given in an Appendix to an early hydraulics book entitled 'The Hydrostaticks' (1672) by George Sinclair of Edinburgh. The rarity of such accounts (see Levine & Wrightson (1991) and Clavering (1994) for relevant reviews) means that Sinclair's description merits quoting at length. The Ravensworth Close coalmill comprised three chain engines, each driven by its own waterwheel. Sinclair (1672, p. 299–300) described the three-wheel system thus:

> '. . . For procuring a fall of water, which may serve the wheels
> of all the three sinks [i.e. shafts], [Sir Thomas Liddel has] erected
> the first work [i.e. water wheel] upon pillars like a wind-mill,
> pretty high above ground, from which the water falling
> makes the second go close above ground. And to make the water fall
> to the third, the whole wheel is made to go within the surface of the
> ground, which terminates at a river under the works [i.e. a tailrace adit],
> which mine is of a considerable length . . .'

Elsewhere in his text, Sinclair (1672, p. 298) gives some details of subsurface arrangements of a coalmill, which though not specifically stated to relate to the Ravensworth Close system can be confidently assumed to do so:

> '. . . there is first one [shaft] 40 fathom deep from the grass.
> Another in a right [i.e. straight] line from that, of 24.

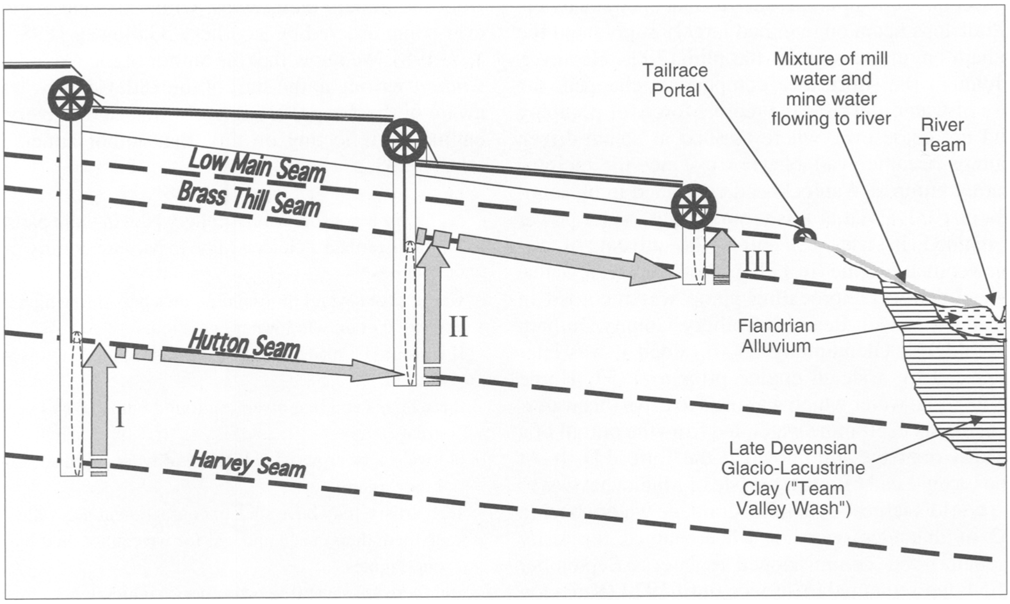


Fig. 2. Ravensworth Close coalmill of 1672: a geological cross-section of the site of this three-wheel chain engine dewatering system. The section has been developed by adding modern stratigraphic knowledge to the verbal description of the system given by Sinclair (1672). Notes: I, II and III are the three vertical lifts by the rag-and-chain pumps, which are represented by the dashed lines in each of the three shafts. The grey block arrows show the progress of the pumped water from the deepest workings to daylight at the portal overlooking the River Team.

Another of 12; upon all which there are water-works [i.e. water wheels].
In the first sink the water is drawn from the bottom 12 fathom,
and thence conveyed into a level or mine, which carries it away to
the second sink. By the second work, the water is drawn out of the
second sink 14 fathom, from the bottom, and set in by a level
to the third sink, which being only 12 fathom deep
the water-work sets it above ground . . .'

Figure 2 reproduces this description in the context of our modern geological understanding of the area (as summarized on British Geological Survey 1:10560 Sheet NZ 25 NW). From the stratigraphic configuration now deduced for this site, it is clear that the Ravensworth Close coalmill was well located to dewater several square kilometres of workings to the west of the hydrogeological barrier represented by the Team Valley Wash, a buried valley immediately to the east of the site which is plugged with glacio-lacustrine clays (Fig. 2).

Wheels were not the only device used to harness water power for pumping from mines. Bucket-operated balance beam engines were apparently widely used in the mid- to late-18th Century, when they were documented in operation in Cornwall, Staffordshire and Scotland, operating in both coal and metalliferous mines (e.g. Robey and Porter 1972, p. 27–30). Vernacular terms applied to these devices include 'flop-jack' (in Cornwall), 'balance bob', 'bucket engine', 'tub engine', and (in Scotland) 'Bobbin' John'. A sole surviving example of the genre remains to this day, at the former Straitsteps lead mines, Wanlockhead (Scotland) (Although records of bucket-operated beam engines at this site date back to 1745, the surviving example is probably of mid-19th Century construction; Anon. 2002). The Straitsteps engine consists of a stone column fulcrum on which is balanced a long timber beam. At one end of the beam is a large bucket, which was positioned to receive surface water diverted via a launder from the nearby Wanlock Burn. At the other end of the beam, a pivot provided a connection to a pump plunger which worked a reciprocating pump deep underground in a mine shaft. As the water bucket at the free end of the beam filled to capacity, it outweighed the pump plunger at the far end of the beam and sank downwards, shedding its load. By this means, the pump plunger was raised within the rising main, drawing water up to the point where it decanted from the main into a shallow adit, where it mixed with the water spilled from the bucket and flowed away to the Wanlock Burn.

Reciprocating pumps, such as that operated by the Straitsteps beam engine, had largely supplanted the 'chain engine' design by the mid-1700s. However, although the subsurface components changed, the use of water power as the motive force for pumping did not cease everywhere as soon as steam-driven pumps became available. For instance the reciprocating pump at Wanlockhead continued in use until about 1931. Even in less remote areas, water power remained in use well after the advent of the Newcomen Engine (in 1712). For instance, a waterwheel-driven reciprocating pump was recorded in action in 1844 at Beamish Colliery, County Durham (Hair 1844; Glendinning 2000) (albeit it was later replaced by a steam engine prior to 1857; Horne 1993). The water which was used to drive this waterwheel was itself mine water, led from the outfall of a nearby drainage adit known as the Telford Drift. At the Laxey Lead Mine on the Isle of Man, what was to be world's largest-ever mine drainage waterwheel (a 22 m diameter overshot wheel named the Lady Isabella) was commissioned as late as September 1854 and remained in service until 1929 (Kniveton 2000). The pumps driven by the Lady Isabella routinely raised 19 $l s^{-1}$ of water from a depth of 365 m, and it has been estimated that this required only 20% of the wheel's maximum power output. The magnificent Lady Isabella and associated beam engines remain in full working order and today serve as a major tourist attraction.

Mine dewatering in the age of steam

In recounting the surprisingly late persistence of waterwheel-driven pumps, it is not intended to understate the importance and overwhelming popularity of steam-driven pumps for the dewatering of mines all over Britain. The first tentative steps towards the economically-viable raising of water by steam power were taken in the 17th Century, with the granting of a patent on 17th January 1631 to one David Ramsay for an invention 'to raise water from low pits by fire' (Galloway 1898, p. 196). However, nothing seems to have come of Ramsay's invention. Experiments by physicists working in the Low Countries and France, most notably Huyghens and Papin (Galloway 1898, p. 236–238), paved the way for the next attempt at full-scale harnessing of the power of heat, which was made public on 25th July 1698, when Thomas Savery obtained a patent for his 'Miner's Friend'. This steam engine met with a certain degree of success in large-scale experiments, but it proved both inefficient and dangerous in the real working environment of coal mines. In particular it proved incapable of raising water more than about 10m without running the risk of a boiler explosion, and since this was far less than the 73m limit of water-driven coalmills then in existence, the 'Miner's Friend' never enjoyed a reciprocal amity from the miners themselves, with only one engine ever being ordered by a colliery (Galloway 1898, p. 197–198). We know that the author of the *Compleat Collier*, writing at the start of the 18th Century, was aware of the disappointing performance of Savery's engine. In reflecting on this, that author lamented ('J.C.' 1708, p. 18–19):

> '. . . were it not for water, a collery [sic] in these parts,
> might be termed a Golden Mine to purpose, for dry collieries
> would save several thousand pounds per Ann. which is
> expended in drawing water hereabouts . . .
> If it would be made apparent, that as we have it noised abroad,
> there is this and that invention found out to draw out all great
> old waists, or drown'd collieries, of what depth soever; I dare assure
> such artists, may have such encouragement as would
> keep them their coach and six, for we cannot do it by our engines,
> and there are several good collieries which lye unwrought and drowned
> for want of such noble engines that are talk'd of or pretended to . . .'

As it turned out, the author of the *Compleat Collier* did not have long to wait, for it was in 1712 that Thomas Newcomen, of Dartmouth in Devon, constructed the world's first, full-scale steam-based engine to successfully dewater a colliery (the 'Dudley Castle' engine at Coneygree Colliery, Tipton, South Staffordshire; see discussion in Rolt & Allen 1997). Within the next two years, further Newcomen engines were installed at Bilston (near Wolverhampton), Hawarden (Flintshire, North Wales) and at Griff Colliery (Warwickshire). The engine at the latter site cut the annual costs of dewatering (which had previously been achieved using horse gins) by more than 80% (Galloway 1898). Such major cost savings soon became trumpeted throughout the land, and within the following eight years, Newcomen Engines were constructed in most of the mining districts of Britain. The 'drowned collieries' of NE England were in the vanguard of the rush of investment in the new technology, fulfilling the desires expressed not ten years previously in *The Compleat Collier* ('J.C.' 1708). The earliest known pictorial representation of a Newcomen engine is dated 1715 and hails from Tanfield Lea Colliery in County Durham (Atkinson 1966, p. 26). Newcomen Engines were erected at several other NE collieries before 1720 (at Washington, Ravensworth, Byker and Elswick) and by 1724, a northern agency for the construction of steam engines had been established at Chester-le-Street (Galloway 1898, p. 243). By 1740, Newcomen engines in Scotland were documented as raising water over vertical distances as high as 146 m (Clerk 1740, p. 24), albeit such a high lift required the use of four stages of 36.5 m each.

Given the overwhelming association in popular imagery of steam engine houses with Cornwall, it is ironic that the uptake of Newcomen Engines was much more widespread in the coalfields of northern England and Scotland than in the copper and tin mines of Cornwall before 1741. This disparity was due to the fact that the sea-borne coal needed for steam-raising was heavily taxed by the English Government at the time (whereas land-scale coal was not and was in ready supply in the coalfields). When the sea coal taxes were suspended in 1741, Cornwall experienced a boom in the construction of Newcomen Engines (Buckley 2000, p. 35). By about the same time, Newcomen Engines were being erected in France (Galloway 1898, p. 244), and soon thereafter in other countries of the European mainland. From small beginnings, nothing short of a revolution had hit the field of mine dewatering throughout the industrialized world, and the Newcomen Engine was to reign supreme for some 60 years.

The next major step in the development of steam-based pumping came in the 1760s in Scotland, when James Watt reflected on the relatively wasteful use of steam in the Newcomen process. The design improvements which Watt developed resulted in the double-acting rotative steam engine, which at a stroke improved the power and economy of the steam engine. Following on from the first full-scale demonstration of the new engine for dewatering of the Burn Pit, Kinneil (Scotland) in 1784, the history of steam technology took on a new trajectory (McKechnie & MacGregor 1958). With steam power no longer restricted just to mine dewatering duties, the age of steam haulage had dawned, which by 1804 had led to the development of locomotives for surface mineral haulage and by 1822 was laying the foundations for the modern passenger rail network (Leifchild 1853).

The new opportunities afforded by the availability of powerful, reliable steam-driven pumps allowed the exploitation of coal and ore reserves on a scale not hitherto possible. One hydrogeological consequence of this boom in mining was the creation of regionally-interconnected systems of mined voids, which in some instances eventually came to be connected over straight-line distances in excess of 50 km (Younger *et al.* 2002). With mined systems interconnected on this scale, it soon became logical to push for regional coordination of mine dewatering operations. For instance, this was advocated as early as 1857 by T. John Taylor, a prominent member of the North of England Institute of Mining Engineers, who devised a specific plan for the integrated dewatering of the entire Tyne Coal Basin between Newcastle and Tynemouth (Taylor 1857). The substantial water management problems of this district in the first half of the 19th Century, to which the proposals of Taylor (1857) were a response, have been documented by Galloway (1904, p. 7–8). Taylor's original proposals were not implemented in the Tyneside coalfields at the time, largely due to the chronic fragmentation of interests amongst the many mine owners operating in the area.

Far more successful was the integrated drainage of the South Staffordshire Coalfield (Redmayne *et al.* 1920). By the mid-19th Century, some 320 km^2 of inter-connected workings in this area were experiencing a total water make on the order of 2.6 m^3s^{-1} (Waller 1867). Prior to the 1870s, individual contributions to this total water make were handled individually by each of the collieries in the area. However, disastrous inrushes at Coneygree Colliery (near Tipton) in 1865 and at Highbridge Colliery in 1871 (see Table 1) provided overwhelming evidence in favour of a regional-scale dewatering operation. On 21st July 1873, the first of what would eventually be eight specific Acts of Parliament to facilitate the establishment of an integrated dewatering system for the South Staffordshire Coalfield was enacted. Four distinct drainage areas were identified in the 1873 Act, within each of which a number of individual 'pounds' (i.e. underground catchments) were mapped, providing the geometric basis for planning the deployment of pumping engines. Nearly 50 years after the establishment of this impressive dewatering system, a thorough review of the operational success of the scheme resulted in the recommendation of only a few minor changes to the drainage arrangements (Redmayne *et al.* 1920); that the original design had proven to be so robust is a ringing endorsement of the sound understanding of mine water hydrology possessed by South Staffordshire mining engineers in the second half of the 19th Century.

District pumps within mines

Thus far in considering pumping we have focused on the final act of removing water from a mine by pumping from a shaft sump. However, much of the pumping effort in a mine is expended in gathering water from remote districts of the workings and delivering it to the principal dewatering sumps. As manual bailing soon becomes impractical within cramped underground workings, small pumps have long been used for gathering water from working areas (Sinclair 1958). We know the Romans used Archimedean screws and *noria* for such purposes in mainland Europe (Flores Caballero 1981). Simple hand-operated pumps on the rag-and-chain principle were certainly used in British mines until at least the mid-19th Century (Fig. 3a). Where the quantity of water to be handled was substantial and deep adits were available for gravity drainage of the lifted water, permanent underground waterwheel installations were used. A splendid reconstruction of one of

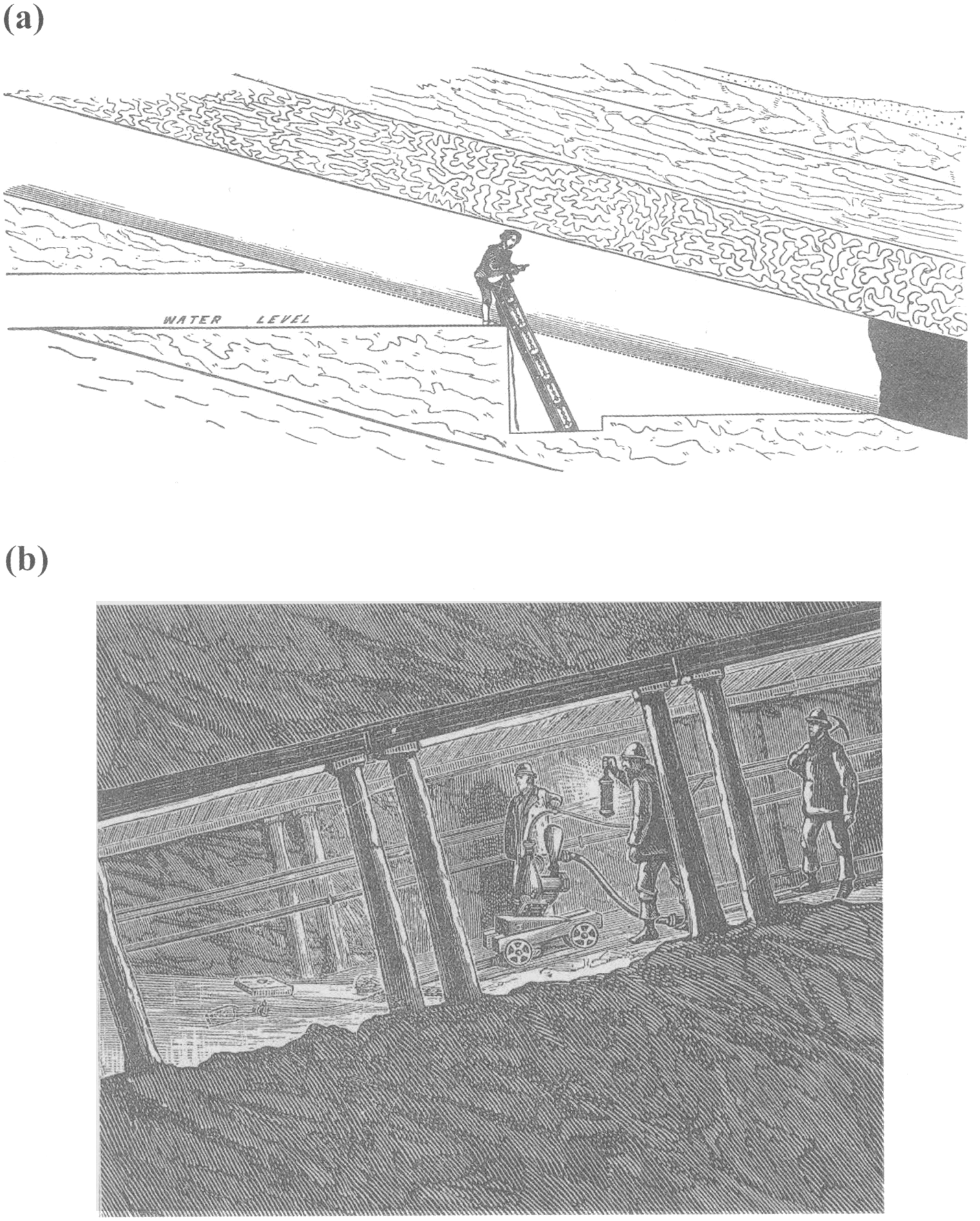


Fig. 3. (**a**) Portable rag-and-chain pump in use to locally drain a working area in the early 19th Century (from Taylor 1858). (**b**) A portable 'Pulsometer' steam pump in use at the tail of the water in coal workings in the late 19th Century (from Pamely 1904).

these underground waterwheels may be viewed in operation within the Park Level Mine at Killhope, the North of England Lead Mining Museum (Weardale, County Durham).

Nowhere was the use of underground waterwheels more intensively developed than in the lead mines of Allenheads (Northumberland), where no fewer than six installations were in use by the end of the 19th Century (1923). Figure 4 summarizes the Allenheads dewatering system. Water was

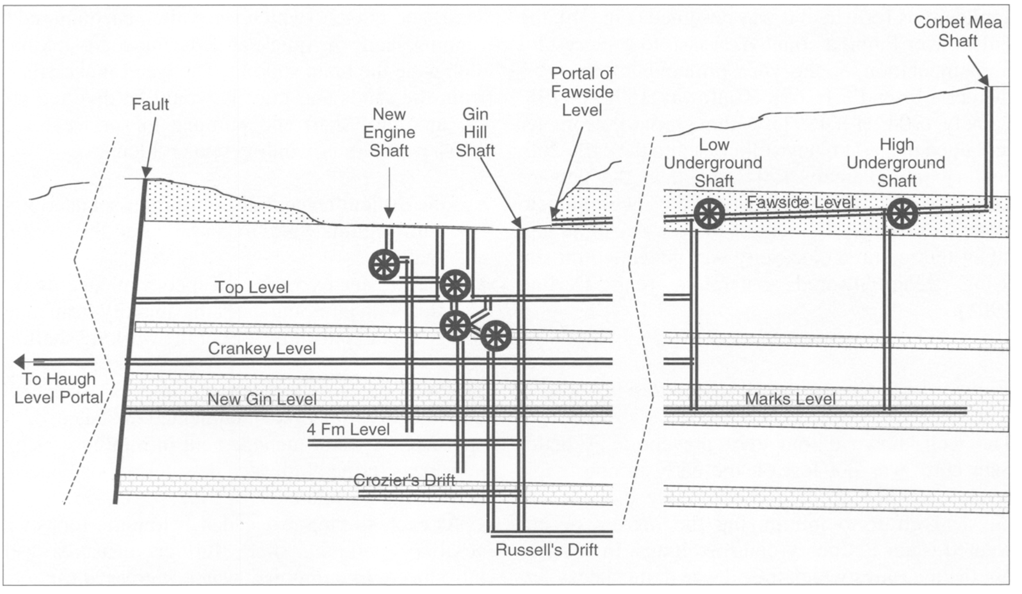


Fig. 4. Simplified synoptic cross-section showing the use of underground waterwheels in the Allenheads lead mine, Northumberland, in the late 19th and early 20th Centuries, developed from more detailed information on specific portions of the whole system presented by Smith (1923) (details in the vicinity of the Gin Hill Shaft) and Dunham (1990) (details between Corbet Mea Shaft and the Fawside Level portal). For an explanation of the sequence of operations see the text. The geological ornament shown relates to specific aquifers. The stippled beds are sandstones of the Firestone Sill. The brick ornament denotes three limestone aquifers, which (from highest to lowest) are the Little Limestone, the Great Limestone and the Four Fathom Limestone.

deliberately introduced to the mine from a surface reservoir via pipes in the Corbet Mea Shaft, and carried in-bye to drive two waterwheels (at the High and Low Underground Shafts). Beyond the Low Underground Shaft, the driveage water and mine water which had been raised by the pumps from Marks Level in the Great Limestone aquifer) was allowed to flow by gravity along the Fawside Level, whence it reached daylight at the adit portal, immediately east of the main Allenheads mine yard. After being used for mineral washing on the nearby dressing floor, the same water was despatched underground once more via the New Engine Shaft (Fig. 4), whence it fell over four separate waterwheels in series, each of which drove a separate reciprocating pump which together lifted water more than 120 m from the deepest workings up to the Crankey Level. Here the pumped water mixed with the wheel-driving water and flowed by gravity for a further 2 km underground, to daylight at the portal of the Haugh Level (an old drainage adit dating to 1684).

As we have seen, steam power was adopted for pumping shaft sumps as early as 1712. However, the difficulties of building, operating and maintaining bulky steam pumps in cramped mine workings appears to have hindered the adoption of steam power for localized pumping within mines until the late 19th Century. In surface-based pumping arrangements (using either waterwheels or steam engines to supply the motive force) it was relatively common practice by the 1850s to operate pumps at some distance from the power source using overland rods which changed the sense of reciprocating movement by means of t-shaped bobs. (An excellent example of this approach survives in working order at Laxey, Isle of Man; Kniveton 2000). Taking a cue from this practice, Moore (1872) described the installation and successful use of a 700 m system of underground rods in Kinneil Colliery, Scotland (incidentally the same site where James Watt first demonstrated his new steam engine design), which transmitted reciprocating action from the vertical rods in the shaft across a number of high- and low-points in a series of mine roadways, to work pumps installed in certain down-dip workings which were prone to flooding. Although successful, the use of extensive underground systems of rods occupied space in cramped mine roadways which could better be used to facilitate coal haulage etc. To overcome this limitation, a truly automated steam-driven pumping technology for localized pumping within mine workings was finally introduced in 1878, in the shape of the 'Pulsometer Pump'. In the low-lift applications for which it was designed (Fig. 3b), the Pulsometer Pump amounted, at last, to a successful implementation of the core principle of Savery's 'Miner's Friend' of 1698 (Galloway 1898, p. 198; Pamely 1904; Hill 1991). Although the Pulsometer remained in use at many collieries into the early 20th century (e.g. Pamely 1904), by then the onward march of electrification was already beginning to make its mark on the field of mine water pumping, albeit the required electricity was generated on-site using steam-powered generators (e.g. Darling 1901).

Physical barriers to minimize water ingress

The well-known axiom that 'prevention is better than cure' was not lost on the early mining engineers, and they devoted considerable thought and physical effort to minimizing the ingress of unwanted water to underground workings. In describing the measures which they devised, it is necessary to distinguish between those implemented during the sinking and equipping of shafts, and those implemented during active working of coal or other minerals.

Minimizing water ingress during shaft sinking

As evidenced above, by the late 17th Century mine water pumping techniques had become sufficiently well advanced that it was possible (in all but the most permeable ground) for mines to proceed to depths of several hundreds of metres below the pre-mining water table. However, as the most easily-worked strata were gradually exhausted (Levine & Wrightson 1991), mine exploration inevitably migrated to locations where it was necessary to sink shafts through considerable thicknesses of saturated, permeable strata before mining could commence. One of the earliest settings in which this took place was in the axis of the Tyne Valley, where unconsolidated sand and gravel deposits of Quaternary age overlie the Coal Measures. As these permeable deposits are not exposed above the high water mark (being extensively blanketed with late Devensian glacio-lacustrine clays) it appears that their presence was at first unsuspected by engineers sinking shafts along the banks of the Tyne. The earliest attempted sinkings through these heavily-watered sands and gravels met with failure and records dating from 1637–1638 report that three pits sunk on the Tyne floodplain near the first colliery boomtown of Whickham had succumbed to closure on account of insuperable water makes in the preceding two years (Levine & Wrightson 1991, p. 40–41).

Methods for coping with these problems soon emerged. Where possible, an auxiliary pumping shaft would be sunk into the problematic saturated sands and gravels (which were often encountered as running sands or 'quicksand' during shaft sinkings) alongside the main sinking. The water make arising from the sands and gravels would be diverted into the auxiliary shaft and pumped to surface ('J.C.' 1708, p. 13), thus avoiding two problems:

- the difficulties and discomforts associated with allowing this water to cascade into the working shaft;
- the greater expense and inconvenience associated with pumping the same quantity from much greater depth at the foot of the working shaft.

The use of auxiliary shafts in this manner is undoubtedly the first documented instance of an approach to water management in mining which is nowadays termed 'advance dewatering' or 'external dewatering' (Younger *et al.* 2002, p. 206–211).

As each sinking proceeded below the foot of its auxiliary pumping shaft, further measures were introduced to minimize water ingress during the sinking of shafts. Thus the author of the *Compleat Collier* stated ('J.C.' 1708, p. 18–19):

> '. . . For framing back our Shaft Feeders, we make use of Wood, but chiefly Firr [sic], because . . . we think it swells with the Water lying against it . . . we make use of Sheep-Skins with the Wool on . . . which, being well Wedged in between the frame and such rough Mettle, &c . . . we find to perfect our Design of stopping the Water . . .'

Already, somewhat more sophisticated approaches were under development. It would appear that stone coffering was in use in some of the coal mines of Shropshire by 1698 (Galloway 1898, p. 223). By 1708, iron frames were introduced to add strength to the timber packing at Harraton Colliery (near Birtley, Co. Durham) ('J.C.' 1708, p. 13). However, for most of the 18th Century, iron frames were not widely used for shaft lining (Galloway 1898, p. 258). Instead, advances in the engineering of wooden linings proceeded to the point that well-coopered timber linings were proving capable of holding back water with driving heads of 70 to 100 m (Galloway 1898, p. 311). These timber linings comprised:

(1) horizontally-oriented 'cribs' or curbs of 0.2 m-square timber, which were fastened to the rock walls of the shaft at vertical intervals of 0.6 to 0.9 m, forming closed rings around the circumference of the shaft, to which were nailed;
(2) tightly-jointed, vertically-oriented planks of wood (up to 75 mm thick and 3 m long).

Because of its resemblance to well-made wooden tubs, this form of shaft lining came to be known as 'tubbing', a name which persisted even after the preferred lining material ceased to be wood.

At shallow depths, or where the strata being excavated yielded little water, the use of brick and mortar shaft linings became commonplace during the early 19th century. For lining-out unconsolidated deposits and water to depths of ten to twenty metres, brick walling founded on timber cribs was used in combination with a sealing fill of puddled clay, which was pressed into the annulus between the brick wall and the rock face of the shaft. This was the system employed, for instance, in the sinking of the Plas Power Collieries near Wrexham (North Wales) in the 1870s (Griffith 1876). By the end of the 19th Century, brick-lined shafts were being constructed to considerable depths (Pamely 1904, p. 101–103), but rarely with much success and never cheaply where the sinking had to contend with substantial aquifers. For such heavy-duty applications, cast-iron tubbing became the favoured option for most 19th century mining engineers.

The pioneer of cast-iron tubbing was John Buddle, one of the great early 'Viewers' (i.e. colliery engineers and managers) of the 18th and early 19th Century coal trade in NE England. During the sinking of the Wallsend A Colliery (Northumberland) in 1792, Buddle overcame the now-familiar problems with saturated Tyne Valley sands by designing and installing cast-iron tubs, which in this first application were cylinders manufactured to closely fit the excavated circumference of the shaft, (Galloway 1898, p. 311). Three years later, the nearby King Pit at Walker (Northumberland) was lined in the same manner. However, as the use of cast-iron tubbing spread, it soon became evident that single-piece, cylindrical iron tubs were extremely difficult to manipulate except in the shallowest of applications. Buddle responded to this by designing segmented iron tubbing which could be easily lowered into place then joined together *in situ* until the entire circumference of the shaft had been lined. This improved technique was first implemented during the sinking of the adjoining Percy Main Colliery (Northumberland) in 1796–1799 (Galloway 1898, p. 312).

Notwithstanding the success of cast iron tubbing in Buddle's sinkings, it had its drawbacks. Foremost amongst these was cost, which was considerably more than for conventional wooden tubbing. Secondly, although it was introduced on the grounds that it was far stronger than wooden tubbing, it was not infallible, as evidenced by the Houghton inrush of 1832 (see Table 1). Furthermore, when employed in upcast ventilation shafts, many of which in the early 19th Century were still driven by shaft-foot furnaces and therefore carried damp air as hot as 170°C, cast-iron tubbing rapidly rusted. For these reasons, wooden tubbing continued to be used in shaft sinking well into the 19th Century (Galloway 1898, p. 295).

Cement was also proposed as an alternative to cast-iron tubbing, on the grounds that it was cheaper and far less prone to degradation under the conditions likely to be encountered in upcast shafts (Watson 1861). This proposal caused considerable controversy (Anon. 1861; Atkinson 1861), principally because the attainable strength of cement rings was far less than that required for the safe tubbing of very high water pressures then being encountered in deep sinkings in the concealed coalfield of Durham (Atkinson 1861; Atkinson & Coulson 1861). Using experimental data provided by Watson (1861) on the strength of cement rings, Atkinson (1861) was able to demonstrate that under 180 m head of water cement rings would crumble, whereas cast-iron tubbing had by then been known to withstand water heads far in excess of this figure for more than 150 years. In the event, it was to be well into the 20th century before that offspring of simple cement, mass concrete, was successfully developed as the shaft-lining of choice (e.g. Forster Brown 1924).

Throughout the 19th century, the mining engineers of the Durham Coalfield were in the vanguard of endeavours to develop major coal reserves inferred to be present beneath major, bedrock aquifers. In the concealed, eastern half of the Durham Coalfield, the strata which unconformably overlie the Coal Measures are of Permian age, and consist of up to 200 m of dolomitic limestones (the Magnesian Limestone) overlying a highly variable thickness (from zero to tens of metres, over distances as short as one or two kilometres) of well-sorted, poorly-cemented sands of aeolian origin (the Yellow Sands). Both the Magnesian Limestone and the Yellow Sands are prolifically permeable, providing between them a substantial component of the public water supply in east Durham to this day (Younger 1995). The experiences gained in battling the Magnesian Limestone and the Yellow Sands in the Durham Coalfield not only paved the way for later sinkings through the Bunter Sandstones of Yorkshire, Derbyshire, Nottinghamshire, Staffordshire and Lancashire, but also provided many of the crucial insights upon which 20th century undersea mining was so successfully founded.

A full account of the many mishaps suffered and lessons learned by the bold pioneers who joined battle with the aquifers of the Durham Permian would require a separate paper and thus only a brief summary can be given here. The earliest attempted sinking through the Durham Permian was at Hetton in 1818. So severe were the water problems encountered when the shaft entered the Yellow Sands that the sinking had to be abandoned. After a re-think, a new start was made in 1821. Despite thorough tubbing, the water make which had to be dealt with was as high as 150 ls^{-1}. By the end of the 19th

Century, a total of 20 successful sinkings had been made through these aquifers (Bell 1899; Atkinson 1902), virtually all of which had been achieved only after major struggles at the limits of contemporaneous pumping and tubbing technologies (e.g. Potter 1856; Anon. 1857; Wood 1857).

During the first half of the 19th Century, the use of tubbing to exclude water from deep shafts proceeded according to 'close topped' designs, in which each tier of tubbing would be completely sealed top and bottom against the water-bearing strata. This was achieved by building each tier of tubbing up from a foundation ring (termed a 'wedging crib') which was firmly set into the shaft wall and sealed against the base of the tubbing structure by means of a gasket. Installation of such close topped tubbing is well-described from a number of sinkings in the eastern half of the Durham Coalfield (e.g. Atkinson & Coulson 1861; Pamely 1904), and generally proceeded as follows:

(1) at a point where a wedging crib was required, the diameter of the shaft would be increased (by manual pickwork, rather than blasting) by 30 or 40 cm to provide a groove into which the crib could be slotted;
(2) segments of iron wedging crib (typically 15 cm hollow square section girder) would be inserted into this groove and wedged together (using oak wedges) until it formed a complete ring which tightly fitted the circumference of the shaft and protruded by about 50 mm or so to provide a ledge upon which tubbing could be founded;
(3) the first course of cast-iron tubbing segments would then be installed on the ledge. 'Sheeting' made of bark would be first laid on the crib, which would deform under the weight of the tubbing segments and form a tight seal. The tubbing segments were typically 0.6 to 0.9 m in vertical dimension and sized and shaped so that ten to twelve of them would complete the circumference of the shaft. Neighbouring segments were designed with inter-locking flanges so that they would fit tightly together without the need for bolting;
(4) five or six succeeding courses of tubbing would be built up, forming a tier between 3 and 6 m in total height, and the uppermost course of tubbing segments in the tier would be tightly sealed (using more bark sheeting) against the sole of the overlying wedging crib (which formed the base of the next tier);
(5) pressure-relief holes were usually present in each segment, which allowed water and gas to escape until the entire tier of tubbing was complete, after which wooden wedges and plugs would be installed to make the tub watertight.

Such tubbing was installed selectively in any given shaft, to case-out any loose and/or saturated strata which would otherwise collapse and/or feed water into the shaft. It was common practice to raise several tiers of close topped tubbing through selected intervals of problematic strata. These tubbed intervals would generally be interspersed with unlined sections of shaft, or sections only lightly dressed with a skin of brickwork or timber lining.

As this technique was implemented against ever-greater hydraulic heads during sinkings through the Magnesian Limestone and Yellow Sands in east Durham, severe problems began to be encountered, amounting to 'the most critical and dangerous source of failure in the tubbing employed to shut off large feeders of water often encountered in the sinking of mines; the blowing out of the sheeting, and displacement of the tubbing, by the pressures of the water and gas confined behind it, in cases where [the tubbing] is close topped' [i.e. tightly sealed top and bottom] (Atkinson & Coulson 1861). At the very least, this sort of displacement made the shaft walls uneven and therefore hazardous for cage haulage operations. In some cases, the pressure of water and/or gas was so great that segments of the tubbing were entirely dislodged and fell down the shaft, breaking shaft fittings and threatening the lives of miners below. Observations of such cases by Atkinson & Coulson (1861) revealed that once the pent-up pressure had obtained some vent, further disturbance of the tubbing was not experienced. A number of strategies were therefore developed to relieve excessive pressure before it could damage the tubbing. These are of hydrogeological interest because they demonstrate a working knowledge of the non-hydrostatic nature of ground water head in heterogeneous aquifers. The three strategies were:

(1) to open up small bleed holes through the tubbing and allow a certain amount of water to enter the shaft, and fall to the sump where it would be picked up by the pumps. It was found that only a relatively small proportion of the feeder which had originally been tubbed-out needed to be allowed to enter the shaft in order for substantial local relief of pressure behind the tubbing to be realized;
(2) to exploit natural differences in head between different tiers of tubbing to provide pressure relief without drainage into the shaft. This was achieved by the use of 'pass pipes' connecting the top of one tier of tubbing to the base of the next, and so on to the top of the tubbed interval, where the uppermost tier was always open-topped (there being no overlying wedging crib into which the uppermost course could have been sealed). This effectively destroyed 'the

isolation of the water behind the different lifts or tiers, [making] them common, one to the other; and thus, in effect, [rendering] the whole of the tubbing open topped, through the medium of the uppermost lift, which is so, in fact' (Atkinson & Coulson 1861, p. 10);

(3) in cases where build-up of gas was suspected to be the principal threat to the tubbing, a pipe would be inserted through the tubbing and raised up the shaft to such a point at which the water level settled. This pipe then allowed gas to bubble up and escape through the open end of the water pipe without the inconveniences associated with draining the water into the shaft.

Each of these strategies was implemented on various occasions by Atkinson & Coulson (1861). In relation to the first strategy, during the sinking of Castle Eden Colliery in southeastern Co. Durham (which took place in 1836; Wade 1998) a 128 m interval of tubbing had been installed to deal with feeders originating in the Magnesian Limestone. No new feeders were encountered in the first nine metres of sinking below the basal crib of this tubbing interval. Then a new feeder of some 11.3 ls^{-1} was encountered, which was quickly tubbed back up to the overlying basal crib and sealed tightly. However, within 36 hours, the build-up of pressure behind the new tubbed interval dislodged some of the tubbing segments. Repeated repairs were made, but the dislodgement always recurred. Eventually, a tap was fitted through the tubbing which allowed a flow of 0.01 ls^{-1} to enter the shaft (i.e. less than 0.1% of the rate of the feeder which had been tubbed-out). No further dislodgement of tubbing ever occurred during a 25 year period of observation. A similar experience at Harton Colliery (South Shields, Co. Durham), where the main source of excessive pressure was methane being released from the saturated strata, met with success when a number of taps through the tubbing were allowed to drain methane and some 0.2 ls^{-1} of water into the shaft (Atkinson & Coulson 1861).

A second attempted sinking in the vicinity of Castle Eden (SE Durham) provides an instance of the second strategy, i.e. inter-connecting separate tiers of tubbing so that they all act as if they were a single open-topped tub. Brick walling to a depth of about 26 m had been used to exclude drift deposits from the shaft. About 3.6 m into the underlying Magnesian Limestone, a water strike occurred, which was eventually tubbed-out by an interval of tubbing founded at 88 m depth and carried up for 62 m to the base of the brick walling. Some 7 m below the basal crib of this tubbing, a horizontal tunnel was driven through the Magnesian Limestone to intersect the base of a shallow, secondary shaft being sunk nearby. This tunnel encountered no water whatsoever. However, on deepening the main shaft a further 5 m below the invert of the tunnel inset, water was encountered once more, this time yielding a substantial feeder of some 38 ls^{-1}. The close topped tubbing which was installed to exclude this water from the shaft was inter-connected with the uppermost interval of tubbing by means of two 230 mm diameter 'pass pipes'. This precaution having been taken, no displacement of the tubbing occurred.

By 1850 'Sinker Coulson' (as William Coulson was called locally) had successfully sunk 11 shafts through the Magnesian Limestone and Yellow Sands of Co. Durham (in addition to a further 19 shafts on the exposed coalfield in Northumberland and Durham) and his reputation was beginning to spread far beyond his native County (Wade 1998). In 1855, Coulson's expertise was called upon by mining entrepreneurs in the Ruhr Coalfield of Germany, where sinkings were now migrating to the exposed coalfield of the Emescher Valley, where the Cretaceous Chalk aquifer overlies the Coal Measures. On March 17th 1855, by way of a St Patrick's Day Celebration for his dedicated team of Anglo-Irish miners, Coulson began the sinking of the Hibernia Colliery in Gelsenkirchen, near Bochum. Extensive tubbing was employed to get the shaft through the main body of the Chalk with its prolific feeders of water, the shallowest of which entered the sinking at a depth of only 11 m below ground level. It was on entering the Greensand aquifer at 100 m below ground level that Coulson and his team found their opportunity to really make history. Encountering a feeder of 42 ls^{-1}, well-sealed close topped tubbing was installed throughout the Greensand interval, a pipe range was connected to a tap through the tubbing and led back up the shaft. Coulson was going to see just how much head was driving this feeder. To his surprise and delight, the water continued to flow from the end of the pipe range even after it had been raised 3.6 m above ground surface (and some 15 m above the shallowest feeder encountered during the sinking of the shaft). Not only had Coulson demonstrated the presence of supra-hydrostatic head in the Greensand aquifer at this location, he had also provided the new colliery with a free source of good quality water, which was captured in a reservoir and used to supply the needs of the site for many years (Atkinson & Coulson 1861; Wade 1998).

Having demonstrated that water could flow upwards from depth where the head conditions were appropriate, Sinker Coulson proceeded to demonstrate his working knowledge of the hydraulics of perched aquifers during the sinking of the South Wingate Colliery in the southeasternmost extremities of the Durham Coalfield. The Quaternary sequence at this site comprises 11 m of clay overlying 20 m of saturated sand (which yielded 5.3 ls^{-1} to the sinking shaft). This sand is in turn underlain by a further 15 m of clay, below which some 49 m of unsaturated Magnesian Limestone were sunk through before the water table was finally reached 95 m below ground level. Realising the opportunity which this situation afforded, Coulson arranged to capture all of the water from the Quaternary sands in a pipe which was led down the shaft and connected into the open top of the tubbing which was installed through the saturated zone of the limestone. The Magnesian Limestone was sufficiently permeable that the addition of more than 5 ls^{-1} of water from the Quaternary aquifer made no difference to water levels behind the tubbing. Water which would otherwise have been pumped at considerable cost was therefore discharged into the Magnesian Limestone aquifer free of charge (Atkinson & Coulson 1861, p. 16–17).

Following the death of Sinker Coulson in 1865, the use of the close topped tubbing system which he had perfected continued to enjoy enthusiastic uptake. The technique reached its apogee in 1869, with the sinking of the Shireoaks Colliery in Nottinghamshire (near the point where that county meets Derbyshire and South Yorkshire). The excavation of the 553 m Shireoaks shafts through two prolific aquifers (the Triassic Sherwood Sandstone and the Permian Magnesian Limestone) was achieved only after the installation of 155 m of cast-iron tubbing (Pamely 1904). The technique subsequently continued to be applied throughout Britain well into the 20th Century.

Having introduced vented, close-topped tubbing to the Ruhr Coalfield in 1855, mining engineers in NE England were the first in Britain to benefit from the return of a favour when, at the very end of the 19th Century, newly-developed German techniques for shaft sinking through aquifers by means of ground freezing were introduced for the sinking of two shafts at the Washington Glebe Colliery, County Durham. The hydrogeological challenges at this site related to the presence of some 24 m of unconsolidated, highly permeable sands of Quaternary age overlying the Coal Measures (Anon. 1902). The contract for ground-freezing at the site was awarded to the specialist firm Gebhardt und König, of Nordhausen, Germany. The contractors started work on the site in the autumn of 1901 and ground freezing commenced on 23rd March 1902 by means of a variant of the Poetsch method (Pamely 1904, p. 83–85). A steam driven compressor was used to cool liquid ammonia, which was then used in heat exchangers to chill magnesium chloride brine to between -8 and -11°C. The brine was then circulated through circular arrays of boreholes drilled beyond the full depth of the saturated sand around the perimeters of the two proposed shafts. The sand was frozen to a diameter of about 1.5 m around each of these boreholes, forming a dam of solid ice. Within the centre of each shaft, the sand remained unfrozen and was therefore easily excavated, with the 24 m of sinking to the underlying clay horizon being accomplished in only two weeks.

The second successful application of ground-freezing to shaft sinking in the UK was in the far more challenging setting of a new coastal colliery at Dawdon in East Durham (Wood 1907). The Dawdon shafts were sunk on a cliff-top plateau overlooking the North Sea. At this site, 109 m of Magnesian Limestone and 28 m of Yellow Sands overlie the Coal Measures (the two being separated here by a 1m thickness of mudstone known as the Marl Slate). Ground water in the Magnesian Limestone at this point was found (from its salinity and tidal piezometric behaviour) to be in hydraulic continuity with sea water. Sinking through the Magnesian Limestone proceeded by the time-honoured techniques of cast-iron tubbing (68 m of which were required) and pumping at rates of up to 533 ls^{-1} (Wood 1907). The two Dawdon shafts (named the Castlereagh and Theresa Shafts) had reached a point just above the Marl Slate by December 1902, at which point the sinking through the Yellow Sands was placed in the hands of Gebhardt und König, fresh from their successful sinking at the Washington Glebe Pit. The freezing process proceeded in precisely the same manner, with the exception that the greater target depth (and therefore higher geothermal temperature) necessitated cooling the brine to even lower temperatures than had been used at Washington, specifically between -13.5°C to -17°C. Seven months passed before the ice wall around the shafts was deemed to be complete, and sinking through the Yellow Sands re-commenced in the Castlereagh Shaft on November 7th 1904. In contrast to the case at Washington, the sands in the centre of the shaft were found to be so heavily frozen that explosives had to be used to proceed with the sinking. The sinking to the Coal Measures (whence conventional sinking could resume) was completed after 10 months work in each of the two shafts. Temporary wooden linings were used in both shafts to minimize the risk of rock falls during working. Apart from a short-lived scare when a pocket of highly-pressurized unfrozen water was struck by a drilled sump hole, resulting in a temporary 6 m-high fountain of cold water in the base of the Castlereagh Shaft, both sinkings proceeded without hindrance. Basal wedging cribs were installed in Coal Measures shale, 2 m below the base of the Yellow Sands. Cast-iron tubbing was carried in tiers back up from this crib to the base of the lowermost tubbed interval in the Magnesian Limestone. The annulus between the backs of the tubbing segments and the shaft wall was filled with concrete to an average thickness of 11 cm. Thawing of the ice walls around both was undertaken carefully, with active warming of the air in the shaft by slowly raising and lowering of a brazier, and by circulation of warm brine in the former freezing boreholes. After allowing for venting of any trapped gases from behind the tubbing, the shaft lining was sealed and found to be secure throughout (Wood 1907).

Since these two pioneering efforts, ground freezing has been used for sinking many more shafts in the UK. While the efforts sometimes ended in tragedy due to inrushes from unfrozen aquifers (see the case of Easington in 1903, in Table 1) the technique has generally been implemented with sustained success, most recently in the development of the Selby Coalfield (North Yorkshire) in the 1980s.

Following the consideration and rapid rejection of cement as a component for pre-cast tubbing in the early 1860s (Watson 1861; Anon. 1861; Atkinson 1861), as discussed above, it seems that no concerted efforts were made to implement cement-based solutions for the exclusion of water from shafts until 1911, when the use of cementation was introduced to British shaft-sinking circles by Mr Albert François, who had perfected the technique when sinking to coals beneath the Chalk aquifer in Belgium and France. The essence of the technique is to sink an array of sub-vertical boreholes, splaying radially from the projected shaft centre, into which grout is injected under pressure, sealing up the native fissures in the rock such that an effectively impermeable annulus is formed within which the shaft can be sunk with minimal difficulty (Forster Brown 1924). Hatfield Main Colliery near Doncaster was one of the first shafts to be sunk in this manner, successfully sealing back otherwise formidable feeders in the Permian dolomites and sandstones of that district. Over the years, variations on this approach were gradually developed, culminating in the mass-concrete lined shafts typical of the most modern collieries today, in which concrete liners are cast *in situ*, with back-grouting sealing any remaining gaps between the liners and the adjoining rock mass.

Minimizing water ingress to active workings

The evolution of methods to minimize water ingress during working was experientially driven, largely by reflections on some of the more devastating of the inrushes listed in Table 1. Common sense suggested that 'supported' methods of mining, in which pillars are left in place to support the roof, would be far less likely to result in significant induction of water inflows from above than the alternative 'caving' methods of mining, in which pillars were extracted (or never left in the first place) and the roof was allowed to fall. Events such as the 1837 inrush at Workington, in which winnowing of pillars below the sea-bed led to a devastating inrush, only served to underline this intuition. As experience grew, regulations were developed governing the 'safe' dimensions of supported workings and/or the minimum cover needed for caving workings. The first time such regulations were codified in a law was in 1877, following the inrush at Tynewydd (Table 1), in an amendment to the Regulation and Inspection of Mines Act of 1860. This new regulation stipulated that 'where a place is likely to contain a dangerous accumulation of water, the working approaching that place shall not at any point within forty yards of that place exceed eight feet in width' (Coulshed 1951). It was not until the 1920s that regulations governing safe working distances beneath the sea bed were introduced.

From the earliest days of industrial scale mining, it had been widespread (though not universal) practice for miners driving roadways in areas where old workings might reasonably be expected to drill ahead in an attempt to prove any flooded workings before the roadway got so close that the barrier of intervening ground might fail catastrophically. For instance, in writing about the copper and tin mines of Cornwall in the three decades of rapid development of deep workings following the dramatic expansion of steam-driven pumping in the County in the 1740s, Pryce (1778) commented that:

> '. . . In some places, especially where a new adit is brought home to
> an old mine, which has not been wrought in the memory of man,
> they have unexpectedly holed to the house of water, before they
> thought themselves near to it, and instantly perished . . . I think
> where they are tolerably acquainted with their situation, much danger
> may be avoided, by keeping three or five borier [sic] holes before them,
> radiated or displayed above and below, to the right and to the left, from
> the center [sic] of the adit . . .'

However, even where such precautions were taken, complete safety could not be assured. For instance, the devastating inrush at Heaton Colliery (Newcastle Upon Tyne) in 1815 (Table 1) took place despite precautionary drilling having been implemented (Dunn 1848). Another problem associated with drilling ahead of advancing workings in the early 19th Century was the problem of the boreholes themselves providing a route for a devastating inrush. This problem was later overcome by the invention of non-return valves on drilling strings (the fore-runners of the blow-out preventers now routinely used also in the petroleum industry) and by 1860 drilling ahead of advancing workings became a legal requirement in all situations where old workings were even remotely likely to be present

(Coulshed 1951). Eventually, mining engineers became sufficiently skilled in such drilling techniques that they were developed beyond a mere precautionary tool to a means for tapping into, draining and putting back into production areas of old workings which had previously been flooded and abandoned. Wilson (1901) gives a detailed account of the draining down of workings at Wheatley Hill Colliery (SE Co. Durham) which had previously been abandoned following the inrush of water which occurred on 19th January 1871 (Table 1). This was achieved using the Burnside Boring Machine, a local invention which included one of the world's earliest blowout preventers (patented by a Mr G Burnside in 1891, a few months after a similar device was patented by a Mr J Cowey; see Hughes 1904, p. 34–35).

Beyond the establishment and proving (by drilling) of natural rock barriers between active workings and bodies of water (natural or impounded in old workings), the technology of shaft tubbing gradually came to be expanded into geotechnical endeavours to dam unwanted waters back in old workings. At first, these endeavours were limited to closing shaft insets to worked-out seams and installing tightly-wedged tubbing at the interface with the shaft (e.g. Taylor 1858). However, given that the permeability of the flooded workings would offer no sort of 'throttle' on the release of water into the workings in the event of a tubbing failure, this practice was eventually discontinued, to be replaced by the construction of more substantial dams of simple design. One such 19th century example was described from the re-opening of George Stephenson's old workplace at Wylam Colliery, Northumberland, in the early 20th Century (Heslop 1994). Early dam designs tended to comprise two brick walls with clay packed between them. By the 20th Century, more formal designs involving reinforced concrete and rock grouting had largely supplanted these *ad hoc* approaches. Details of such techniques are beyond the scope of this paper, but technical details of such dams as constructed at the close of the 19th century are given by Pamely (1904).

Mine water quality – some early descriptions

At the start of the 21st century one of the principal drivers for sustained interest in the hydrogeology of mined ground relates to issues of water pollution (Younger & Robins 2002), arising from the fact that many mine waters carry dissolved loads of contaminants (especially metals such as Fe, Al, Zn etc.) at concentrations which are much higher than are generally permitted in industrial effluents entering receiving watercourses. These concerns, though very much in keeping with the contemporary environmental agenda of the developed world, are of course nothing new. During the very first phase of coal mining on an industrial scale, at Whickham (Gateshead, Co. Durham) in the early 17th century, numerous grievances concerning the effects of rapidly-expanding coal mines on the natural drainage of the area were raised in a legal deposition dated April 1620 (Levine & Wrightson 1991, p. 110–116). While many of these concerns related to the drying up of wells and springs under-drained by the new adits, water quality issues were also of major concern to the plaintiffs:

> '... two hundred acres and above [of good *meadow land had been*] quyte spoiled and cankered with the water that issueth out of the colewaists ...'

Similar complaints mentioned the 'unwholesome, cankered and infectious' water that flowed from the drainage channels of the mines, which were deemed to have polluted the receiving land surface so badly that grass would no longer grow there, resulting in streams that were so polluted that even the beasts of the field would refuse to drink their waters or to eat grass grown by such streams. Nor were these water quality problems restricted to the Great Northern Coalfield. Further north still, in the Midlothian Coalfield (Scotland), Sinclair (1672) noted that the miners were in the habit of referring to mine water as 'the blood of the coal', a clear allusion to the red tinge associated with high concentrations of iron.

Whereas the coal miners of the north were quick to recognize the 'unwholesome' nature of their local mine drainage, a century later (1760) we find the even more polluted mine waters of Parys Mountain (Anglesey, North Wales) being lauded for their supposed medicinal virtues (Rutty 1760; Rowlands 1966):

> '... [the mine waters are considered] as a powerful detergent, repelling, bracing, styptic,
> cicatrizing, anti-scorbutic and deobstruent medicine, as hath appeared
> by the notable cures they have effected, not only by external use in
> inveterate ulcers, the itch, mange, scab, tetterous eruptions, dysenteries,
> internal haemorrages [sic], in gleets, the fluor albus, and diorhea [sic],
> in the worms, agues, dropsies and jaundice ...'

Not a bad set of claims for Britain's most acidic mine waters, which to this day have a pH of 2.3 and carry extremely elevated concentrations of many toxic metals!

A few years later, in the copper and tin mining districts of Cornwall, Pryce (1778) was also disposed to celebrate the salubrious quality of several local mine waters, lionising in particular those of then-abandoned copper mines named Pednandrea and Huel Sparnon. The effluent from several abandoned adits was captured and used for domestic water supplies, apparently to no ill effect (Pryce 1778, p. 11):

> '... in twenty-four years of acquaintance with the practice of medicine,
> I have not met with any one patient, whose disorder I could attribute
> to the most trifling unwholesomeness in our mine waters ...'

Pryce (1778) then goes on to admit that not all Cornish mine waters are as agreeable, noting that mines excavated into veins below the 'gossany bed' (i.e. zone of oxidation) 'do produce water fit for no use but driving mill or engine wheels. Such water is quite noxious, and palpably vitriolick [i.e. acidic] to the taste, particularly at the mines of North Downs, Chacewater and Huel Virgin'. Interestingly, these are amongst the major mines which to this day contribute to the acidic drainage emanating from the Great County Adit in the Carnon Valley (Buckley 2000; Table 2).

One particular experience recounted by Pryce (1778) is worthy of mention here for the echoes it provokes in those familiar with Cornwall's last working mine (South Crofty, which closed in 1998; see Adams & Younger 2002). Pryce (1778) notes: 'In Huel-Musick and Huel-Rofe, the writer has stood with one foot in the warm and the other in the cold water, and has divided and diverted them different ways'. The present author had precisely the same experience at more than 800 m below ground level in South Crofty Mine in 1997, where at one point in a roadway traversing the Great Crosscourse, one hand could be held in a warm dripper while the other received cold water from an immediately adjoining dripper of entirely different water quality.

Perhaps the earliest reference to a direct economic use for the dissolved constituents of mine waters, (long pre-dating the various instances listed by Banks *et al.* 1996) dates from the early 1770s and relates once more to the Parys Mountain copper mines (Rowlands 1966). It was around that time that it was realized that native copper could be precipitated readily from the highly acidic mine waters simply by inserting scrap iron into the water. In only a few seconds, native copper was reduced from the Cu^{2+} to the Cu^0 state by the zero-valent iron (which was itself oxidized to the Fe^{2+} and Fe^{3+} forms in the process). This early example of reductive precipitation, which nowadays underpins the use of zero-valent iron in permeable reactive barriers and similar remediation facilities, was subsequently harnessed for economic copper production at this site and at the Avoca Mines in Ireland.

One of the first thorough descriptions of hetereogeneous water quality in mines was made by Armstrong (1856) in relation to the mine waters of Wingate Grange Colliery, in the southeastern Durham Coalfield. He distinguished between three types of mine water:

- saline waters, of calcium chloride facies, which he considered may be genetically connected to sea water;
- ferruginous ('chalybeate') waters, which he unhesitatingly ascribed to pyrite oxidation processes, and;
- clean fresh waters not noticeably different from ordinary ground waters in the area.

The elevated iron content of the second type of water developed in a particularly unequivocal manner. Clean water had been induced to enter the pit from the overlying Yellow Sands following pillar removal in underlying seams. This water was not in itself ferruginous, but it flowed into the mine at variable rates which at times were so prolific (up to 140 ls^{-1}) that the instantaneous pumping capacity of the mine was exceeded and the water had to be stored in an area of standage which was set aside in old workings in the Low Main seam. When the water was released from this standage, it was found to have become acidic and highly ferruginous. The concerns which this caused were not related to the environmental consequences of its disposal (as would be the case with such waters today) but solely to the problems of clogging and corrosion of pumping and other equipment to which it gave rise (Armstrong 1856). The clogging of pipes by iron oxide precipitates was then (e.g. Swallow 1891) as now (e.g. Parker 2002) a considerable problem in mine water management and as such it prompted considerable efforts to minimize the effort and expenditure needed to counteract it

Ochre deposits were not the only precipitates observed to clog pipes. In a number of collieries in Northumberland and Durham, rapid precipitation of barytes took place within pipe ranges due to the mixing of two types of mine water (Edmunds 1975):

(1) deep, saline mine waters which were highly enriched in dissolved barium, but devoid of significant sulphate, and;
(2) shallower-sourced mine waters which had acquired high concentrations of sulphate through contact with oxidizing pyrite.

As barium rapidly precipitates to form barytes in the presence of sulphate, with barytes being in equilibrium with only about 1 mgl^{-1} of dissolved barium, circumferential precipitates of barytes developed within wooden 'water boxes' (Dunn 1877) and circular, cast-iron pipes (Clowes 1889). Inspection of these barytes precipitates revealed them to be zoned in seven-layer cycles, with six black-stained layers followed by one off-white layer. These layers correspond to the six working days in the mine, when the air and water are heavy with coal dust, and the well-observed Victorian Sabbath (Sunday), when pumping continued in the absence of coal production. In recognition of this pattern, the miners named these deposits 'Sunday Stone'.

In the course of describing the draining-down of old flooded workings at Wheatley Hill Colliery (Co. Durham) in 1900, Wilson (1901) left to posterity one of the first detailed descriptions of the processes of the oxidation of sulphide and iron following aeration of mine water which had long been trapped in old workings (where bacterial sulphate reduction had evidently occurred). On discharging the water into ventilated workings, an odour of hydrogen sulphide was noticed (and its identity proved using lead acetate test papers). The water also proved slightly acidic to litmus paper. To touch, the water was 'soapy feeling' and it had a 'sickly taste'. Initially it was milky white in appearance, due to the presence of tiny bubbles formed as gases came out of solution, but later ran clear. As it flowed along the mine roadway, it first precipitated a 'white slimy deposit' (which later analysis showed was elemental sulphur) and then, downstream, red iron hydroxides. These sequential precipitation reactions, described by Wilson (1901) for what was almost certainly the first time in relation to mine waters, now form part of the armoury of geochemical reactions which present-day engineers are attempting to harness for purposes of passive treatment of polluted mine waters (e.g. Younger *et al.* 2002).

Technology transfer: sinking, pumping and tubbing enter civil engineering practice

The strong links between early mining engineering and the development of civil engineering could form the subject of an entire book. Rieuwerts (1962) provided the first formal reflection on this topic. 40 years later, much detail remains to be added to this account, particularly in relation to interactions between the mining and water engineering sectors. Here, only a brief introduction to this topic can be given, highlighting a few activities in which the mining engineers can be demonstrated to have transferred their technology and skills to the nascent water and geotechnical engineering sectors.

Shaft sinking and adit driving techniques developed for mining purposes were already being widely adopted for purposes of developing public-supply ground water sources by the middle of the 19th century. To many mining engineers, the joys of developing shafts in which they did not have to achieve the exclusion of nearly all of the surrounding ground water had an irresistible attraction. During the second half of the 19th century purpose-madc water-supply shafts were being sunk by mining engineers (to typical mining dimensions) across the outcrop of the Magnesian Limestone Aquifer in Co. Durham. With the exception of the Ryhope pumping station, at which the ground water became saline due to sea water ingress, all of these pumping shafts remain in use today as part of Northumbrian Water's resource base. At a number of mid-19th Century colliery sites in the English Midlands, mine shafts shafts sunk through the Sherwood Sandstones were deliberately designed to intercept the fresh ground water and divert it to public supply use. Many of these shafts remain in use to this day by Severn-Trent Water, and interesting issues are now beginning to arise in relation to their long-term future once their host collieries are abandoned.

Mining technology was also adopted in the driving of horizontal adits from the sumps of large-diameter wells, particularly in the Chalk. However, it remains to be determined whether the adits in the Chalk were developed by engineers with personal experience of mining, or whether the form of these structures is an instance of 'convergent evolution'.

One key element of technology which undoubtedly originated in the mining sector and was subsequently transferred to the water supply sector was steam-driven pumping. The evolution of steam pumping technology has already been discussed above. Following the innovations of Watt and co-workers in the final quarter of the 18th Century, the cost of steam-pumping technology had fallen by about 1800 into a price range which made it economically attractive for water supply purposes. It then enjoyed rapid uptake throughout the UK water industry, interestingly aided by the professional inputs of Robert Stephenson (Waller 1872), the famous son of the great George Stephenson, who had first liberated the steam engine from the bounds of collieries to serve the wider needs of society. Throughout the 19th Century, there was no professional dividing line between mine water pumping technology and water supply pumping technology (Watkins 1979). Thus it is no surprise to find that one of the earliest forums in which the performance of water supply pumping stations was presented for technical discussion by a *coterie* of interested engineers was the North of England Institute of Mining and Mechanical Engineers (Waller 1867,1872).

The nascent geotechnical engineering sector of the 19th century enjoyed vigorous interchanges of both methodologies and personnel with mining engineering. Two examples typify opposite ends of the spectrum in terms of the successful integration of mining-derived techniques in subsurface construction projects: the Thames Tunnel and the Severn Tunnel.

The first Thames Tunnel, which connects Rotherhithe and Wapping, is famous for its associations with Marc Brunel (1769–1849) and his world-famous son Isambard Kingdom Brunel (1806–1859) (Rolt 1957). In one of the earliest attempts to get the tunnel underway (1807), the renowned mining engineer Richard Trevithick (1771–1833) engaged the latest Cornish high pressure steam pumping technology and shaft sinking techniques. This attempt proved to be one of the few failures of Trevithick's otherwise dazzling career. The problem was that ground conditions in the Thames floodplain, where highly permeable Devensian gravels underlie a thin veneer of silty alluvium of Flandrian age, were quite unlike the conditions in the wettest of Cornish mines, where old workings in hard rock are invariably the source of hefty water makes. Thus in Cornwall, as long as you can deal with the quantity of water, the strata will require little assistance to remain upstanding, whereas tunnelling in the Thames floodplain means grappling with unconsolidated deposits which are prone to collapse and enter any pumped void along with the water they release. A new approach was needed, and Marc Brunel devised this: a large, cast iron tunnelling shield which could be jacked forward as the forehead of the excavation advanced. Even with the assistance of this shield, the tunnel still took 18 years to complete – very slow progress in comparison with conventional mine drainage adits which were under construction around the same time (Table 2). The finished product has stood the test of time, and remains in use to this day as a train tunnel.

50 years later, at the other extremity of the Great Western Railway for which Isambard Kingdom Brunel had since become so famous, the construction of the Severn Tunnel commenced in 1873. This project resulted in a far longer sub-water table tunnel (7.5 km) than Marc Brunel's Thames Tunnel, and it dealt with sustained water feeders of several hundreds of litres per second. However, this 13-year project was eventually accomplished by the patient application of the cast iron tubbing and conventional steam-powered pumping techniques which had served the master sinkers of the coalfields so well over the preceding seventy years (Walker 1891).

Concepts of ground water occurrence amongst early mining engineers

Having surveyed the practical responses of the early mining engineers to ground water problems which they encountered, it is fitting to ask what, if anything, these engineers made of the phenomenon of ground water occurrence. As these men were not generally given to philosophical musings, it is no surprise to find that many of them preferred to adopt their views of natural phenomena 'off-the-shelf', from existing strands of thought current in their times. To understand how the mining engineers' conceptualizations of ground water changed over time, therefore, it is necessary to briefly consider how hydrological processes were conceived in the wider world. To 17th and 18th Century engineers in Britain, there were basically three philosophical traditions from which they might choose their preferred explanation of ground water occurrence (Biswas 1970):

- the concepts of the ancient Greek philosophers, particularly those of:
  (1) Plato who considered all springs to be derived from sea water by some mysterious, unobservable process of subsurface distillation within the bowels of the earth, with waters being drawn inland from the seafloor and purified as they pass upwards (contrary to gravity) to reach the Earth's surface as fresh water springs, and;
  (2) Aristotle, who considered that subterranean water was derived by the condensation of mysterious vapours entering in caves and other voids in the subsurface.
- the Judaeo-Christian creation myths, as expounded in the Book of Genesis.
- emerging scientific concepts of the hydrological cycle, in which evaporation of sea water was (correctly) considered to be sufficient to explain the origins of virtually all observed terrestrial ground- and surface waters.

The world's earliest treatise on mining engineering, Agricola's *De Re Metallica* of 1556, admits that some proportion of ground water arises from infiltration of surface waters, but largely adheres to the concepts of subsurface condensation as proposed by Aristotle (Hoover & Hoover 1950, p. 46–48). Thus Agricola claims that steam is generated deep underground and migrates upwards towards the Earth's surface, where it eventually condenses to form water: 'In this way water is being continually created underground'.

In 1708, the author of *Compleat Collier* gave the following explanation of mine water occurrence:

> '. . . all which [mine] Water we suppose to come from the sea, and so being
> fed by that inexhaustible fountain, we call it by the name of a Feeder,
> and that it may rise to the top of any mountain we are subject to believe
> no great Matter of Wonder, because we are so often, by the Curious and Learned,

told, That the Sea, this Fountain Head, is higher than the Earth . . .'

('J.C.' 1708, p. 17–18)

One presumes that the author of this passage had Genesis 1 (verses 6–7) in mind when he considered mine water provenance, since that verse of scripture ascribes the blue sky to the presence of a vault holding back primordial waters from the earth below.

70 years later in Cornwall, Pryce (1778) briefly reviewed the scientific concepts of seawater evaporation and condensation to form rainfall as advanced by Sir Edmund Halley (the astronomer of comet fame), only to summarily dismiss these (without further explanation) as being 'overturned . . . by Mr Derham's perennial spring in the parish of Upminster, and various others in different parts'. He then goes on to exhume the ancient opinions of Plato and dress them up in what was then modern-sounding apparel, arguing that (Pryce 1778, p. 13):

'. . . the only true origin of perpetual springs [is] the Ocean . . .
our hypothesis is that in the formation of perpetual springs
they not only derive their waters from the sea,
by ducts and cavities running from thence through the bowels
of the earth . . . but that the sea itself acts like a huge
forcing engine, or hydraulick machine to force and protrude
its waters from immense and unfathomable depths, through those
cavities, to a considerable distance inland . . .'

Fortunately for his posthumous reputation, Pryce (1778) had the common sense to temper this claim with explicit recognition later in his text that a substantial component of the water make of mines in west Cornwall could be related directly to seasonal rainfall:

'The waters with which our mines abound, are derived
from both temporary and perennial fountains . . .
and are . . . distinguished by the names of Top and Bottom Water.
Shallow mines have very little water, more than comes from
the surface . . . Our very deep mines are subject to water from
both the sources before mentioned . . . in the depth of winter, when
all the earth is drenched as it were with moisture, we are visibly
affected by the concurring streams both of Top and Bottom Water
. . . The deepest of our mines are not much affected by the influx
of Top Water, before the depth of winter; as it takes
till that time, to fill the interstices of the earth or strata,
and protrude its redundant stream to the deep bottoms . . .'

(Pryce 1778, p. 16)

By the 19th Century, most accounts of ground water occurrence in and around mines showed signs of a nascent scientific understanding. Leifchild (1853) in his poetic description of the origins of subsurface waters (quoted above, at the start of the section entitled 'Ground water problems in mining') clearly understood that the waters encountered in deep mine workings were ultimately of atmospheric origin. The engineering specialists of his day, such as Nicholas Wood, William Coulson and John Atkinson, clearly understood the contribution which aquifer heterogeneity can make to vertical variations in hydraulic head within what otherwise would be regarded as a single aquifer. This understanding is evident in the following explanation of why head in the Magnesian Limestone was sometimes found during tubbing to be far greater than would be anticipated simply from the depth below water table (Atkinson & Coulson 1861, p. 10–11):

'. . . [usually] the water behind each lift [i.e. tier] of tubbing
is naturally connected with that behind all the other lifts
in the same shaft, by means of the cavities and gullets in
the strata; so that the pressure of the water on the tubbing,
is that due to the depth from the level of the source of
the highest feeder met with in sinking, to the part of the tubbing
where the pressure is exerted. In many instances, however, this
is practically not the case, owing, probably, to the very long,
tortuous, and contracted channel through which the connection of
the different feeders of water, the one with the other, is established . . .'

This is an eloquent expostulation of the causes and consequences of heterogeneous flow distributions more than a century before these phenomena were formally described and quantified in the mainstream ground water literature (e.g. Freeze & Witherspoon 1967). Nor were Atkinson & Coulson (1861) alone in conceptualizing non-hydrostatic head profiles in this manner. A lively debate which took place at the North of England Institute of Mining Engineers on May 7th 1857, on the occasion of a discussion of the paper by Potter (1856) on the epic sinking at Murton through the Magnesian

Limestone and Yellow Sands aquifers (Anon. 1857), reveals that most of the great mining engineers of the period (Nicholas Wood, T.Y. Hall, Matthias Dunn and George Greenwell) shared the views of Sinker Coulson and his associates.

As we have already seen, Atkinson & Coulson (1861) were sufficiently confident in their conceptualization of heterogeneous flow patterns that they were able to exploit vertical variations in head to install pass pipes and other measures intended to avoid local head build-up behind tubbed sections at depth. They also clearly appreciated the concept of regional drawdown, as revealed by the following comment which they offered on the temporal evolution of water pressure behind close topped tubbing which they installed in the shaft of Harton Colliery (South Shields, Co. Durham): 'Since this shaft was sunk, the establishment of water works at Cleadon has lowered the water behind the tubbing, to the extent of several fathoms' (Atkinson & Coulson 1861, p. 15) (The former Cleadon pumping station lies some 2 km from the site of the Harton shafts).

By the end of the 19th Century, therefore, the mining engineers of Britain had developed and applied a sophisticated understanding of the occurrence and movement of ground water in some of our major aquifers. Unfortunately, their expertise was rarely made accessible to the wider hydrogeological community, and mine water specialists remained largely within their own discrete professional circle. Like many isolated social groups, they developed and maintained their own shared sets of concepts and values, which were often quite distinctive (at least terminologically and sometimes even in terms of physical understanding) from that shared in mainstream hydrogeological circles. This is clearly evident in the language and concepts which were in common use for describing mining-related aspects of ground water flow systems in the first half of the 20th Century. Particularly influential in this period was Saul (1936, 1948, 1949, 1959, 1970), whose classic descriptions of processes of ground water ingress to active workings in the Durham and Yorkshire coalfields influenced the thought and practice of several generations of mining engineers. Saul's papers describe the major factors governing 'normal inflows' (as opposed to catastrophic inrushes) to deep coal mines in the UK. Some of the major conclusions of Saul's work include the following:

(1) mined ground is not so much a porous medium as a network of interconnected 'breaks', principally vertical water-bearing fractures (mostly corresponding to dip-parallel faults and joints), and 'laterals' (such as beds of sandstone or worked seams) (Saul 1948, 1949).

(2) Water makes its final entry into mine workings in a highly localized manner, appearing either as 'feeders' (like underground springs) or as 'drippers' (resembling 'rainfall' from a small area of the roof). The discrete nature of most inflows to mines reflects the pattern of 'breaks' through which water moves through mined ground before it meets a shaft or roadway.

(3) In the absence of adjoining shallow workings or a steeply-dipping permeable sandstone in the sequence, new mine voids deeper than about 140 m (or more than 140 m below the sea bed, or the base of overlying aquifers as appropriate) are unlikely to encounter major feeders (Saul 1948), save where faults provide short-circuiting connections to higher horizons (Saul 1970).

Because of this very particular conception of mining hydrogeology, porous media-based mathematical models were only sporadically adopted and used in mine water management circles. Even Darcy's Law did not remain inviolate, as the meaning of key terms in the formula were bent to fit the peculiar circumstances of deep mining (see Younger & Adams 1999, for further discussion).

The peculiar hydrogeological vocabulary of the mining sector was mentioned in the introductory paragraphs of this paper: 'water makes', 'feeders', 'drippers', 'swallys' / 'swilleys' and 'holings' are only a few of the florid terms which the mine water specialist uses every day, but which are largely foreign to the mainstream hydrogeologist (Younger *et al.* 2002). However, most of these terms have a lineage that greatly pre-dates the more mundane synonyms with which they might be replaced. For instance, the term 'feeder' was used freely by the author of *The Compleat Collier* in 1708, was commented upon for its expressiveness by Leifchild (1853) and remains in common parlance to this day in English-speaking mine water circles. For how many other 'mainstream' hydrogeological terms can such ancient pedigree be claimed?

The author gratefully acknowledges access to the magnificent Nicholas Wood Memorial Library, located in the headquarters of the North of England Institute of Mining and Mechanical Engineers, which has the distinction of being the earliest professional association of mining engineers to be established anywhere in the world. It is an honour and a pleasure to be able to draw on the resources of such an eminent organisation. Dr A. Doyle not only directed me to useful resources in the Nicholas Wood Memorial Library, but also sparked my curiosity with his helpful comments on many aspects of this work. P. Walker of *Pwll Mawr* (Big Pit), the excellent National Mining Museum of Wales near Blaenavon, and R. Lynch of MCG Consultancy Services Ltd (Monmouth), both provided very useful information on Welsh drainage adits for Table 2. I am also indebted to three Keiths, for three different things: to K. Parker of the Coal

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