Westfield pit lake, Fife (Scotland): the evolution and current hydrogeological dynamics of Europe's largest bituminous coal pit lake

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ABSTRACT

The Westfield coal basin was by far the most remarkable coal deposit in Britain, with a very low overburden ratio and enormous reserves. It was the mainstay of the largest and longest-lived opencast coal mine in British history, which was operative for almost fifty years. Post-closure, the site now contains one of Europe's largest pit lakes, and certainly the largest bituminous coal pit lake. Plans for re-development of this extensive site to serve present-day needs for energy generation and waste management depend in part on the dynamics of groundwater movement, and patterns of groundwater quality, beyond and within the site boundaries. Through scrutiny of all available records and analysis of recently-collected data from the site, the evolution of the groundwater system at Westfield to its present condition has been reconstructed. A fascinating story has emerged, involving permeable fault planes and vast bodies of permeable, pyritic backfill. Viewed in the light of this history, it has proven possible for the first time to develop estimates of the proportions of the pit lake inflows derived from various sources, which provides a solid basis for future plans to management pit lake (and thus groundwater) levels throughout this extensive site.

INTRODUCTION

Pit lakes in coal mining environments

There is a substantial literature on the development, geochemistry and management of pit lakes in general (e.g. Castro and Moore 2000; Younger *et al.* 2002; Bowell 2002). A substantial sub-category of this literature relates to pit lakes formed in former surface coal mine voids (e.g. Geller *et al.* 1998 and references therein). However, nearly all of this literature relates to pit lakes in former lignite (soft brown coal) voids, with little or no literature on equivalent lakes in pits of former bituminous (hard) coal mines. The reason for the imbalance of papers between the lignite and bituminous coal sectors is simple: most economically-workable lignite deposits have very low overburden / coal ratios (frequently less than 1), whereas it is very rare for bituminous coal deposits to have ratios much less than about 10. Given the bulking-up of strata which occurs during ripping and tipping in typical opencast operations, it is not very common for bituminous coal opencast mines to leave large flooded open-air voids behind after site restoration. While there are some significant recreational lakes developed on former opencast bituminous coal sites in the UK and elsewhere (e.g. www.rothervalleycountrypark.co.uk), these are rarely true *pit lakes* (i.e. flooded mine voids), but have been purposely formed on and within backfill materials, with beds engineered to lie at a much higher level than the former base of excavation. These recreational lakes are often fed by surface runoff, and do not share the water quality problems common to true pit lakes in pyritic environments.

Purpose of this paper

This paper is essentially a case study of one of Europe's largest pit lakes, and certainly the largest bituminous coal pit lake. The paper documents the developmental history of the void and discusses present-day hydrogeological and geochemical dynamics. The findings illustrate some principles of mine water behaviour which are of general relevance in Carboniferous coal-bearing strata worldwide (in deep mines as well as surface mines).

EVOLUTION OF THE WESTFIELD SITE

Westfield Opencast Coal Site: location and geological setting

The Westfield Opencast Coal Site (OCCS) is located centrally in Scotland (Figure 1), in the northwestern extremity of the coalfield region of Fife. Geographical features of particular note in the vicinity of the site (Figure 1) include Loch Leven (the largest lowland freshwater lake in Scotland, and a National Nature Reserve), the hills which bound the site to the north (which owe their position to the major East Ochil Fault (EOF); see below) and the Lochty Burn, to which all natural site drainage would fall in the absence of pumping. Annual average rainfall in the area is around 900mm, of which almost half (440 mm) is lost to evapotanspiration (Gaus and Ó Dochartaigh 2000).

The general stratigraphic succession of the area is summarised in Table 1, from which it is evident that the Westfield OCCS worked numerous coal seams within the Lower Coal Measures and the Passage Formation (Namurian). Altogether the mined sequence of the Westfield Basin totalled more than 240m of strata ranging from the No 2 Mine Coal (Lower Coal Measures) down through the entire thickness of the Passage Formation as far as the Westfield Upper Lava (which closely succeeds the marker bed for the base of the Passage Formation, i.e. the Castlecary Limestone; Norton 1983). The coal-bearing sequence of the "Westfield Basin" originally comprised some 23 individual horizons of locally thick (but rather lenticular) coals, which together represented a total reserve in excess of 35M tonnes. The overburden-to-coal ratio was in low single figures, a feature which has ensured the persistence of a large remnant void after the cessation of normal backfilling operations.

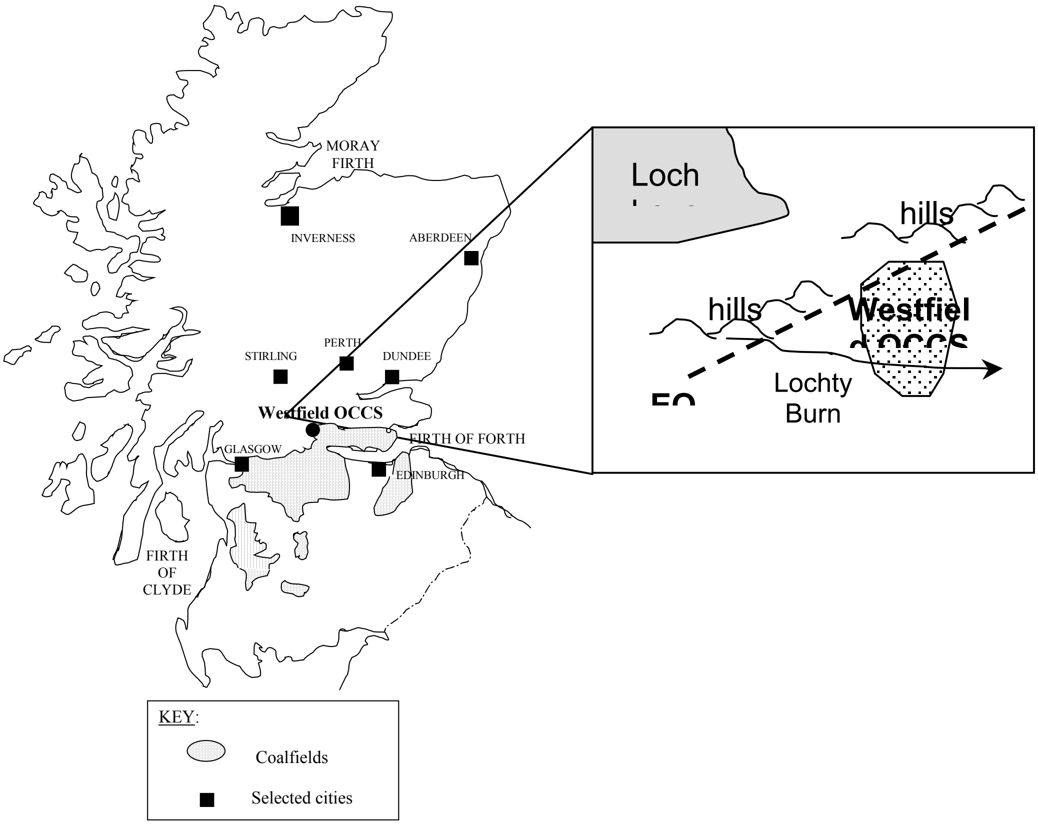


Figure 1: Location of Westfield Opencast Coal Site, Fife, Scotland.

The seams in the Westfield Basin were found to be disposed in a steep-sided synclinorium plunging towards the north-east, where the basin is truncated by the East Ochil Fault (EOF). This major WSW-ENE extensional and transpressive fault displays both a dip-slip throw to the south (estimated at about 2000m; Norton 1983) and major dextral strike-slip displacement (Read *et al*. 2002). The synclinorial structure of the Westfield Basin is itself a consequence of stratal buckling during transpressive deformation of the hanging wall of the EOF. Even earlier in the geological history of the area, down-warping associated with syn-depositional movements along the EOF are considered to explain the unusually great thickness of coal-bearing strata which accumulated within the Passage Formation of the Westfield Basin (Read *et al*. 2002).

The natural hydrogeology of west-central Fife is dominated by the presence of the Fife Sandstone Aquifer (FSA), which is a composite (multi-formational) water-bearing sandstone sequence (Foster *et al*. 1976; Robins 1990; Gaus and Ó Dochartaigh 2000). The closest outcrop of the FSA to Westfield commences little more than two kilometres from the northern highwall, and extends beneath Loch Leven, which is likely in good hydraulic connection with the aquifer. As will be seen, the FSA has had a significant influence on the history of the site.

Table 1 - Summary of the bedrock stratigraphy of central Fife in the vicinity of Westfield OCCS

System	Series	Group	Formation	Comments
CARBONIFEROUS	Westphalian 'A'	Coal Measures	Lower Coal Measures	Six seams in this Formation **worked at Westfield OCCS**
	Namurian	Clackmannan Group	Passage Formation	17 seams in this Formation **worked at Westfield OCCS**
			Upper Limestone Formation	Though extensively worked for coal elsewhere in Fife, these Formations were too deep for opencasting at Westfield
			Middle Limestone Formation	
			Lower Limestone Formation	
	Viséan	Strathclyde Group	Pathhead Formation	The Pittenween, Anstruther and Fife Ness Formations of East Fife are absent here due to overlap on basal Viséan uncomformity
	Tournaisian	Inverclyde Group	Ballagan Formation	Mudstones and volcanics, hosting thick dolerite sills (which also intrude the overlying Pathhead Formation)
			Kinneswood Formation	These four formations together comprise the so-called 'Upper Devonian' Fife Sandstone Aquifer
DEVONIAN	Fammenian	Stratheden Group	Knox Pulpit Formation	
			Glenvale Formation	
			Burnside Formation	
	? Emsian	Garvock Group	Undefined	Conglomerates, sandstones and basalts

Note: summary compiled and updated from unpublished reports of Scottish Coal, re-interpreted in light of recent stratigraphic revisions of the Carboniferous (Read *et al.*2002) and Devonian (Trewin and Thirlwall 2002) of Fife and adjoining areas.

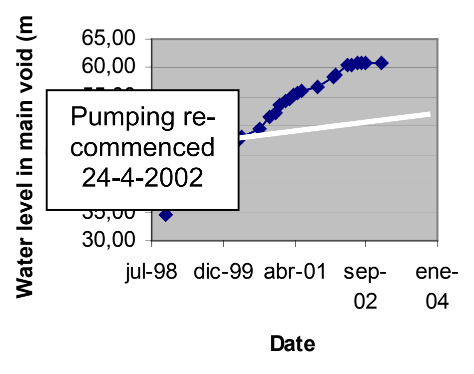
Summary of mining and dewatering history of Westfield OCCS

The layout of the various phases of opencast workings at Westfield is shown in Figure 2. Phase I (26 Mm^3 excavated; 5.4 Mt coal recovered) was worked from January 1961 to September 1968. Phase II (34 Mm^3; 87 Mt coal) worked from October 1968 to October 1973. Pumping records from Phases I and II are extremely sparse; however, it is estimated that 60 to 100 l/s was pumped during most of this period, much of which originated from seven distinct seepage zones mapped on the eastern wall of the void (Norton 1983).

Figure 2: Layout of opencast workings at Westfield (after Norton 1983).

Phase III (52 Mm^3; 8.4 Mt coal) was worked from October 1973 to 1984. At the same time the Extension was worked (10 Mm^3; 3 Mt coal). Extensive data and interpretations presented by Norton (1983) relate to this period. The Extension site is not noted as having significantly increased the overall water make of the site, and the combined makes from the Phase I/II backfill and other sources of water entering the Phase III workings accounted for an average of 110 l/s, or about 84% of the total water make. In fact it was during Phase III that the single greatest increment in site water make was induced when the EOF was deliberately breached as part of slope stabilisation works. Breaching of the 15m-wide shatter zone of the EOF at about sea level resulted in a substantial perennial groundwater inflow to the pit, ultimately sourced from the FSA, with which the EOF is in good hydraulic connection at depth behind the highwall. The inflow induced from this source was estimated by Norton (1983 p. 201) to vary between 38 and 53 l/s, with an average flow of 50 l/s (Norton 1983, p. 193). This estimated range possibly starts at too high a value, as accurate measurements of inflow from the EOF made at the end of a very dry summer in 1984 revealed the water make to the Ochil sump to range between 27 to 32 l/s, with a mean rate of 30.8 l/s (Aspinwall and Co Ltd 1984, pp 31 - 32). Overall, it seems that working of Phase III and the Extension site increased the total site water make by about 64%, of which 56% originated from the EOF, and around 8% from the Extension site. The total water make of the site at the close of Phase III operations was noted as ranging between 113 and 150 l/s (Norton 1983), though peak flows as high as 225 l/s were reported to have occurred prior to the commencement of flooding of the main void (Robins 1990). The Link Site was mined between 1991 and 1996; this was a modest operation removing shallow coal along anticlinal axes, and it is not thought to have materially altered the total water make of the Westfield OCCS.

Given the low overburden-to-coal ratios typical of this extraordinary Carboniferous basin, it was always anticipated that a substantial residual void would remain after the end of coaling and backfilling (which finally occurred in 1998). The residual voids currently remaining on the site are here referred to as the Main Void (which corresponds to the space defined between the EOF highwall and the final loose wall of Phase III) and the East Void (a residual void from Phase I). The formation of pit lakes within these voids was always anticipated, following the suspension of dewatering operations. The question was how long it would take for water levels to rise from the maximum depth (around -80m OD) to reach some "design water level" for such a pit lake. Figure 3 shows observed "rebound" (i.e. water level recovery) rates in the main void over the last few years.



Pumping re-commenced 24-4-2002

Figure 3: Observed rebound rate in the Westfield main void.

Analysis of Figure 3 reveals that rebound rates have varied considerably during the period of record. The overall rebound rate from December 1985 up to the re-start of pumping on 24th April 2002 was 0.77 m/month. It should be borne in mind that some pumping took place in this period, so that the 'natural' rate of rebound would have been even greater than that observed. From November 1998 to April 1999, the short-term rate of rebound (0.70m/month) was similar to the overall rate. The rate of rebound then slackened off for a while (e.g. 0.62 m/month between May 1999 and May 2001, and only 0.19 m/month in the summer period from June to September 2001), only to steepen once again to 0.50 m/month over the winter of 2001/2002. With renewed pumping thereafter, the rebound rate dropped to a negligible 0.064 m/month between May 2002 and December 2002.

CONCEPTUAL MODEL OF PRESENT-DAY SITE BEHAVIOUR

Hydrogeological observations and interpretations

Pumping from the main void recommenced on 24th April 2002, with an installed pump capacity of approximately 150 l/s. This installed capacity equals the peak water makes prior to rebound. As such the pumping provision was prudently designed to cover all contingencies where possible water makes were concerned, and was thus expected to exceed the rate required to maintain steady water levels in the long term. It should be recalled that the head difference between the main void and surrounding strata has been reduced by about 140m since the end of Phase III backfilling, which can confidently be expected to have substantially diminished head-dependent inflows. In corroboration of this inference, it has been found that sustained pumping from the main void at 150 l/s actually leads to a decline in water levels within the main void. Over the last two years it has proven necessary to pump from the void on a part-time basis (60%), in order to maintain steady water levels at around 60m AOD. Scrutiny of pump run-time records indicates that maintenance of the water level within the void at around 60m AOD has been achieved without any pumping at all being required between early July and mid November. With a total of 202 pumping days per annum at a rate of 150 l/s, this means that the total annual water make amounts to around 2.6 Mm3, which would equate to a steady pumping-rate of 83 l/s year-round. From this figure it is possible for the first time to quantify the decline in head-dependent inflows, which has been attained through permitting the flooding of the main void to 60m AOD.

To a rough first approximation, an 86% increase in head within the voids has yielded a 35 l/s decline in groundwater inflow rates (averaging out at around 2.25 l/s of inflow lost for every ten metres of head rise). But which of the two most important sources of groundwater inflow have actually been reduced during rebound, those emanating from the eastern wall, or the yield from the EOF shatter-zone? Until the water level in the main void reached sea-level, there can have been no back-pressure on the flow emanating from the EOF at this elevation in the highwall, and the average inflow rate of 50 l/s will have continued, representing a free-flow response to a head difference of about 105 m AOD (being the difference between the 'fixed-head' in the FSA at Loch Leven and the elevation of the excavated discharge point on the highwall. From Darcy's Law, we know there is a direct proportionality between head difference (Δh) and flow rate (Q), so that we can write:

$$Q = f \cdot \Delta h \qquad (1)$$

where *f* is a constant (with units of m^2/d) which corresponds to the product of hydraulic conductivity (m/d), cross-sectional area through which flow occurs (m^2), and the reciprocal of the flow-path length over which the head difference is manifest (m^{-1}), none of which are individually known in this case. For an average EOF inflow rate of 50 l/s (= 4320 m^3/d), and with Δh equal to 105m, then *f* must be approximately equal to 41 m^2/d. As the components of *f* are head-independent, we can use this same value to calculate values of Q for all other values of Δh. So for 2004 conditions, with Δh = 105 - 60 = 45m, the estimated inflow to the main void from the (now submerged) EOF shatter-zone is 41 x 45 = 1845 m^3/d (= 21.35 l/s). This represents a decline in inflow from the EOF of 50 - 21.35 = 28.65 l/s. As we have already deduced that the overall decline in groundwater inflow to the site to date is of the order of 35 l/s, then the major loss in inflow relates to the EOF (82%), with the eastern wall inflows having reduced only by 35 - 28.65 = 6.35 l/s. This means that under 2004 conditions the eastern wall groundwater inflows (totalling an estimated 38.65 l/s) now exceed the inflows from the EOF - a reversal of the predominance which obtained before the start of rebound.

But is it logical that rates of inflow from the eastern wall would have declined less sharply than those from the EOF. The short answer is "yes". The EOF inflow is effectively an "upwelling" of water from the FSA at depth beneath the footwall of the fault, which enters the void no higher than the horizon at which the excavations exposed the shatter-zone (i.e. about 0m AOD). Hence as water levels rise in the main void, the single inflow horizon of the EOF becomes ever more deeply submerged. By contrast, in the eastern wall, mapping undertaken during the Phase III operations revealed the presence of distinct seepages of groundwater from a total of seven different horizons distributed from the base to the top of the rock wall (Norton 1983), of which four have now been submerged due to the rise of water level in the void. Three discrete seepage horizons remain unsubmerged at present (lying at elevations of 64.5, 73.5 and 79.5m AOD); these will continue to flow unabated until they are finally submerged.

Hydrogeochemical patterns

A considerable amount of interpretative work in relation to the hydrogeochemistry of the Westfield OCCS during the Phase III operations was undertaken by Aspinwall and Co Ltd (1984). Amongst other things, this work demonstrated beyond any reasonable doubt that the water which was sampled entering the site via the EOF shatter-zone originated in the FSA. Although a complete hydrogeochemical investigation of all of the waters presently encountered within the site is beyond the scope of this paper, it is worthwhile briefly reviewing the characteristics of some of the principal waters currently found within the site in comparison to those which were sampled during the early 1980s. Table 2 provides a summary of some indicative hydrochemical parameters for several categories of water at Westfield.

Table 2 - Selected water quality parameters for pit lakes and groundwaters recently and formerly encountered within the Westfield OCCS

Water source	pH	Cond. (μS/cm)	SO_4 mg/l)	Cl (mg/l)	Fe (mg/l)	Ca mg/l)	Mg (mg/l)	Na (mg/l)
Main void pit lake (east) in 1996	2.4	6000	3410	86	422	426	474	9.3
Main void pit lake (east) in 2001	3.5	4846	3716	24	22	392	625	32.5
East void pit lake in 2001	7.6	2198	1149	13	0.3	231	189	9.8
Water flowing from E. Ochil Fault in 1984	7.4	556	46	36	<0.01	39	32	18.5
Backfill groundwater in 2001 (BH4s)	2.9	2890	1840	5	10	333	182	7.8
Backfill groundwater in 2002 (BH3s)	5.8	5100	3860	24	183	516	722	36
Passage Group groundwater (BH6s) in 2001	7.1	1320	326	22	0.01	143	82	16
Inverclyde Group groundwater (BH1d) in 2001	6.6	4400	2710	20	0.02	575	525	25
Lochty Burn upstream of site in 2001	7.1	528	62	30	0.8	47	18	18

A number of key observations arise from scrutiny of Table 2:

(i) In terms of major ion chemistry, both of the present pit lakes are of Mg-Ca-SO_4 facies. Pyrite oxidation is by far the most likely source of the high sulphate concentrations in these lakes, with an upper limit on dissolved SO_4 concentrations in the main void being imposed by equilibrium with gypsum. The very high hardnesses in the two pit lakes likely reflect ankerite dissolution (which yields Ca, Mg and Fe to solution).

(ii) It is clearly important to understand why pH is currently lower, and Fe concentrations higher, in the main void than in the eastern pit lake. The most obvious explanation lies in the presence of a large body of acid-generating washery fines in intimate contact with the southern shoreline of the main void, near its western end. Seepages which can be seen emerging from these washery fines have been observed by the author to display pH values as low as 1.8, and they constitute a localised source of highly acidic water to the overall mixture in the main void.

(iii) There has been a marked general improvement in water quality in the main void over the last 8 years. In terms of major cations and anions, the affinities of the main void waters in 2001 are clearly with the backfill groundwaters, as opposed to the groundwater which was formerly sampled (in 1984) flowing from the East Ochil Fault shatter-zone at around 0m AOD. Although the water remains acidic (pH around 3) iron concentrations are no longer especially high by the standards of many Scottish mine waters (cf Younger 2001). The decline in both iron concentrations and total mineralisation (represented by conductivity) is likely indicative of the gradual submergence of much of the most acid-generating backfill, which is now no longer directly accessible to atmospheric oxygen and is thus less prone to pyrite oxidation. Further increases in water level can be expected to further extend the influence of this beneficial process, especially if it results in permanent submergence of the washery fines discussed under (ii) above.

(iv) Although the water in the eastern void is not as acidic or ferruginous as that in the main void, it is still of relatively poor quality when compared to potable groundwaters pumped elsewhere in Fife. In particular, the highly elevated SO_4 and very high hardness mean that this water is unsuitable for a wide range of potential uses (potable and industrial); these concentrations are also sufficiently high to exert a limitation on biodiversity.

(v) The supposed 'Inverclyde Group' groundwater sampled in Borehole 1d has a hybrid composition, indicative of a mixture of native groundwater (perhaps similar to that which flows into the eastern void from the Passage Group) with leachate emanating from the former coal stockpile area in the northwest of the site. This water illustrates the difficulties of unequivocally identifying the provenance of waters entering the site when it is only possible to drill and test boreholes within the site curtilage.

(vi) The water in the Lochty Burn upstream of the site is reminiscent in quality of the water which formerly flowed from the East Ochil Fault during the early 1980s. This probably indicates natural groundwater discharge to the Lochty Burn from undisturbed groundwater systems to the west of the Westfield site.

In relation to the deductions about rebound processes outlined in the preceding section, it is important to note that:

1. The present hydrochemistry of the site shows far less of an input of good-quality EOF water than was the case during mining, and
2. The eastern void (which is of course the direct recipient of inflows from the eastern wall) persists in showing clear signs of mixing between backfill leachates and water of Passage Group affinities.

Conceptual model

A. The Westfield site is taken to include all of the areas shown in Figure 2, which have been previously disturbed by opencast coal mining activities (including excavation and disposal of overburden materials).

B. The present water make of the two pit lakes, all of which reports to the pump in the main void, totals 83 l/s. This total water make comprises the following components:

(i) Water originating from rainfall within the Westfield site, totalling @ 23 l/s on average

(ii) Groundwater inflowing from the Fife Sandstone aquifer, via the submerged cut into the East Ochil Fault shatter zone (at around 0m AOD in the northern highwall of the site), currently totalling @ 21 l/s on average

(iii) Groundwater inflowing from the Passage Group strata through the eastern wall of the excavation, currently totalling @ 39 l/s.

C. It is assumed that only negligible quantities of groundwater enter the site from the south and west.

D. Water in the eastern void is a mixture of the eastern wall inflow (@ 39 l/s) plus backfill leachates (@ 4.5 l/s annual average) and occasional direct surface runoff (@ 7 l/s annual average). All of the water in the eastern void, which is not lost to evapotranspiration, flows through the western bund of waste rock into the main void.

E. Water in the main void is a mixture of eastern void water (@ 50.5 l/s), water emanating below the water line from the East Ochil Fault (@ 21 l/s), backfill leachates (@ 4.5 l/s annual average) and occasional direct surface runoff originating within the site (@ 7 l/s annual average).

F. The quality of water emerging from the East Ochil Fault is very good; the quality of water emerging from the Passage Group in the eastern wall is moderate; the quality of backfill leachates is poor.

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