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Mine water treatment at Six Bells colliery, South Wales: problems and solutions, from conception to completion

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Abstract

*This article describes the hydrogeological and engineering problems and solutions associated with the completion of the Coal Authority's mine water treatment scheme at the abandoned Six Bells colliery in South Wales. Historically the mine water discharge, arising from the Vivian shaft, was net-alkaline, with an elevated iron concentration (*c.* 50 mg/L), and a flow-rate of approximately 40 L/s.*

Because interception of the mine water at the point of discharge was not considered feasible, a borehole was driven to intercept the mine water at the intersection of two abandoned mine roadways, over 200 m below ground level.

The treatment system comprises two settlement lagoons, operating in parallel, and a tertiary treatment wetland. Because the majority of the iron is present in the ferrous form, a hydrogen peroxide dosing system was also installed, to ensure effective oxidation within a limited land area. Also, hydrogen peroxide would limit the hydrogen sulphide odours around the discharge, which had been a cause for complaints by local residents. The design of the system was necessarily based on the quality and quantity of the uncontrolled discharge.

When pumping from the borehole commenced, the quality of water discharged was significantly worse than that of the uncontrolled mine water, with iron concentrations in excess of 200 mg/L. The hydrological and hydrochemical changes during the pump test are discussed. To ensure compliance with regulatory conditions during early operation, additional chemical treatment, using caustic soda, was required. The pumped water quality has now improved, to a point where caustic soda dosing is unnecessary. Using hydrogen peroxide as an oxidant, the mean effluent iron concentration is currently < 5 mg/L. This residual iron concentration will be further reduced when the tertiary treatment wetland matures.

The implications of the experience of treating the Vivian shaft discharge, for future design of mine water treatment schemes, are discussed. In particular, the advantages of making provision for temporary active treatment at some sites are highlighted.

Key words: caustic soda, design, hydrogen peroxide, maintenance, mine water treatment, pump test, Wales

INTRODUCTION

Until late 2001 one of the most significant mine waters in the UK was that discharging to the Ebbw Fach River, just to the south of Abertillery, South Wales. Although not acidic, the discharge contained approximately 50 mg/L iron, and had a flow-rate typically in the region of 40 L/s. Table 1 illustrates the chemical quality of the uncontrolled discharge during 2001. With the exception of ferrous iron concentration, the data show that the quality of the discharge was very consistent. The flow-rate was also consistent during 2001.

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In terms of iron load, this was one of the worst mine water discharges in the UK. The impact on the receiving watercourse was therefore both severe and widespread. Because of its high impact, the UK Coal Authority included the Vivian shaft discharge (Six Bells colliery) in its allocation of discharges for treatment in 2000. IMC was commissioned to undertake the design and construction supervision of the treatment scheme on behalf of the Coal Authority.

This paper examines some of the difficulties encountered in treating this mine water, and outlines the solutions adopted to overcome them. The lessons learned from the experience illustrate some of the important considerations necessary in designing a mine water treatment system, which go well beyond the selection of the most suitable treatment option based on water quality and quantity alone.

Table 1. Physical and chemical characteristics of uncontrolled Vivian shaft mine water discharge, at Six Bells colliery, during 2001

Determinand	Mean	Standard deviation	n[a]
Flow-rate (L/s)	37.3	1.9	4
pH	6.8	0.2	8
Conductivity (μS/cm)	3424	262	8
Suspended Solids (mg/L)	90	32	8
Alkalinity (mg/L as $CaCO_3$)	764	23	8
Acidity (mg/L as $CaCO_3$)	0	0	8
Chloride (mg/L)	33	3	8
Sulphate (mg/L)	1460	78	8
Calcium (mg/L)	195	17	8
Magnesium (mg/L)	153	12	8
Sodium (mg/L)	446	22	8
Potassium (mg/L)	84.7	3.7	8
Manganese (mg/L)	1.29	0.12	8
Ferrous iron (mg/L)	36.2	10.6	3
Total iron (mg/L)	48.0	2.8	7

[a] Number of measurements made

INTERCEPTING THE MINE WATER

In 1999, IMC undertook a treatment feasibility study for the discharge (IMC 1999). The uncontrolled discharge emerged at the surface immediately to the east of the river. No mining records show the point of emergence to be an adit, or any other mining feature. The close proximity of the discharge point to the Vivian shaft alone suggested that there was a connection between the two, but this was never actually proven until subsequent drilling into the Vivian shaft fill, which resulted in a sudden increase in the suspended solids load of the uncontrolled discharge.

Although there are some shallow coal workings in the area around Abertillery, inspections of old mine plans, and on site investigations around the Vivian shaft, demonstrated the water's origin to be deep workings.

Access and land availability at four potential treatment sites in the vicinity of the discharge was considered. Ultimately the site of a former car sales showroom was selected as the favoured location. Although immediately adjacent to the point of discharge, the site is approximately 10 m above the discharge point, since the river is deeply incised at this point. Design of an entirely gravity fed treatment system was therefore not possible. The preferred treatment site was therefore between the steeply sloping bank of the river and the town of Abertillery.

As well as the usual considerations of land access, purchase and planning permission, an important part of the feasibility study was to assess the best way to intercept the mine water, in order that it could be transferred, by pumping, to the treatment site. Two obvious options presented themselves during the feasibility study:

1. interception of the mine water at the point of discharge by the river;
2. excavation of the fill in the shaft so that a submersible pump could be installed to pump the water from the Vivian shaft.

Ultimately, neither option could be adopted because of the risks associated with them. The uncertain integrity of the conduit through which mine water was carried to the surface meant that it could not be guaranteed that a future blockage of this conduit, possibly resulting in an outburst elsewhere, would not occur. In addition, the pump sump would have been located at the bottom of a steep embankment, next to a river with variable water level.

The Vivian shaft was backfilled in 1962. Again, the structure of the shaft (and in particular the shaft lining) was unclear, and the risk of subsequent problems was considered too great.

Consequently a third option was ultimately adopted. This involved drilling a borehole to intercept a roadway junction within the mine. Directional drilling to a depth of 216 m below ground level was required to intercept this target. The roadway selected was intentionally a cross-measures roadway; since it is driven through host rock rather than Coal Measures, there was more likelihood that this roadway would be in good condition. Also, the former surveyor at the mine had confirmed that the surveyed position on the abandonment plan was accurate. Nevertheless, this strategy of intercepting the mine water also had risks. The main three potential problems were:

1. failing to intercept the roadway junction during drilling;
2. discovering that poor hydraulic conductivity/connectivity between the borehole, roadway and surrounding workings would not allow a sufficient quantity of mine water to be pumped to the surface;
3. finding that there was not a good hydraulic connection between the roadway junction and the conduit carrying the uncontrolled discharge.

If these potential obstacles did not present themselves, it was known that the roadway would prove to be a suitable long-term pumping sump. Thus, in the overall risk analysis of mine water interception and pumping options, this was the preferred strategy.

TREATMENT CONCEPT

After careful assessment of (a) the topography and area of land available at the selected treatment site, and (b) the quantity and quality of the mine water discharge, it was concluded that at this site chemical dosing would be a necessary part of the treatment process.

Local residents and IMC staff visiting the site consistently reported odours of hydrogen sulphide around the discharge. These reducing conditions were consistent with the very high ratio of ferrous to ferric iron. The objective of treatment of this net-alkaline water was therefore to oxidise ferrous iron to ferric iron, in order to precipitate ferric hydroxide at circum-neutral pH. The high ferrous iron concentration meant that a single aeration cascade would not have been sufficient to oxidise all of the ferrous iron to ferric iron. Equally, the topography of the site did not allow for the construction of two aeration cascades and settlement lagoons in series (at least not without additional pumping). Therefore a system was designed that used hydrogen peroxide (H_2O_2) to facilitate oxidation of ferrous iron. Use of hydrogen peroxide would also help to minimise hydrogen sulphide odours associated with the discharge, which had been a cause for complaint by local residents.

In the UK, use of hydrogen peroxide had already proved successful at the Polkemmet mine water treatment scheme, Scotland, and also at the UK's largest open cast coal mine site, in the north east of England (Younger *et al.* 2002).

Following hydrogen peroxide dosing, hydrolysis and precipitation of iron was to occur in a pair of settlement lagoons operating in parallel. Each lagoon has a surface area of 1540 m^2, and a water capacity of 3150 m^3. A tertiary treatment aerobic wetland (2160 m^2) follows the settlement lagoons. For maintenance purposes, both settlement lagoons can be individually bypassed, as can the wetland.

THE PUMP TEST

The basis of the system design was necessarily the quality and quantity of the uncontrolled discharge. In fact a worst case scenario was used, in which the flow-rate was 60 L/s, and iron concentration was 40 mg/L. Nevertheless, there was concern that upon commencement of pumping water quality may change. Certainly, at other sites where mine water has been pumped from abandoned workings to the surface, quality changes have been evident. Most notably this occurred at Frances colliery, Fife, Scotland, where iron concentrations increased by an order of magnitude above shaft water concentrations prior to pumping, during a pump test. In many respects this is analogous to the 'first flush' phenomena (Younger 1997) occurring when uncontrolled discharges first emerge at the surface.

For this reason, it is always preferable to conduct a pump test *before* constructing the treatment system. This enables an accurate assessment of the likely short- to medium-term water quality to be made, and allows the long-term pump-rate to be established.

This was the intention at Six Bells. However, a number of factors contrived to make this approach unfeasible. Most notably, an attempt was made to perform the pump test using temporary treatment facilities, prior to construction of the full scheme. Iron concentrations in the pumped water exceeded 300 mg/L, and consequently the full treatment system had to be constructed first, so that water discharged during the pump test could receive treatment to a quality acceptable to the Environment Agency.

A requirement of the Environment Agency (in order for an abstraction license to be granted) was that a constant rate pump test must be conducted for a period of 14 days. Since the pump rate had to exceed the flow-rate of the uncontrolled discharge for there to be any chance of the uncontrolled discharge ceasing, the constant rate test was carried out at a rate of 60 L/s.

The pump test began in early January of 2002. On 30 January 2002 the pump rate was set to 60 L/s, and was maintained at this rate until 18 February 2002. From 18 February until the present time the pump rate has been maintained at 80 L/s: 30% higher than the treatment system design flow-rate.

The remainder of this paper discusses the hydrological and hydrochemical changes occurring during this

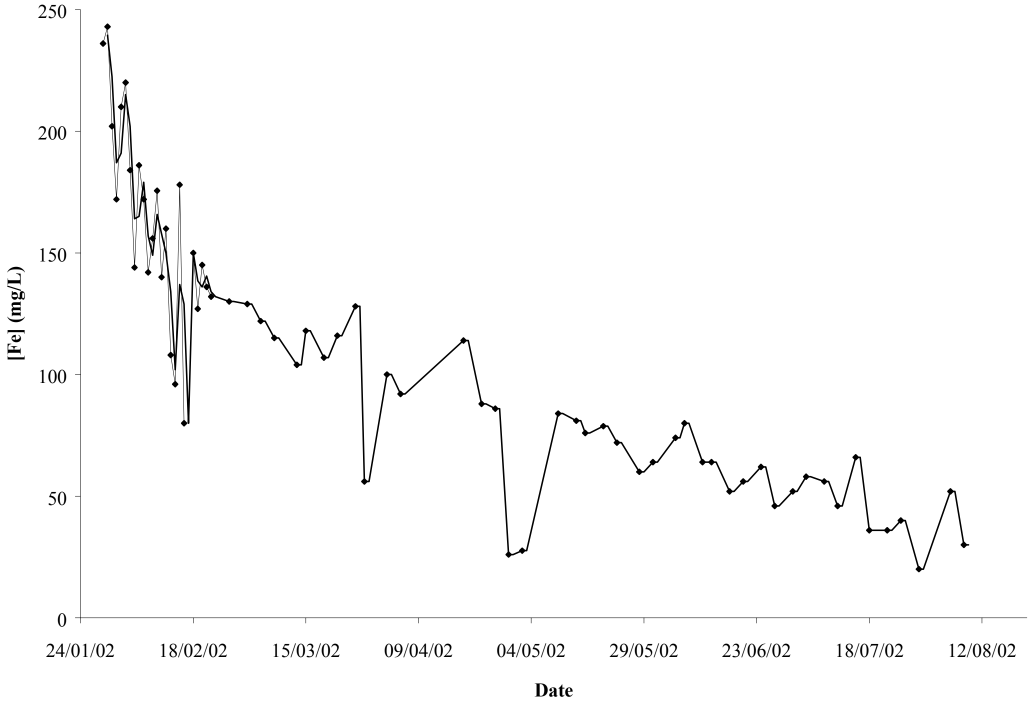

Figure 1. Decreasing iron concentration as pump test progressed at Six Bells

period of pumping (from 30 January 2002 to 17 August 2002), and outlines the approach to treatment required to meet the regulatory water quality limits imposed.

HYDROLOGY AND HYDROCHEMISTRY DURING THE PUMP TEST

Upon commencement of pumping, initially at a rate of 40 L/s, water quality was significantly worse than that of the uncontrolled discharge. The iron concentration of the borehole water was in excess of 200 mg/L. Although the pH was circum-neutral, the water was effectively acidic because of the mineral acidity associated with the iron. Figure 1 shows how iron concentration decreased over the course of the pump test.

This exponential decrease is very similar in its trend to the ‘first flush’ phenomenon referred to earlier. However, Figure 1 shows that in this case pollutant concentration decreases rapidly (in cases of uncontrolled discharges it may be many years before pollutant concentration decreases to an asymptotic level). After six months of pumping, iron concentration returned to that of the uncontrolled discharge. The very poor quality of pumped water experienced during the early months of the pump test had significant ramifications in terms of water treatment. These issues are discussed below.

Prior to pumping, the water level in the borehole was 192.5 m A.O.D. (2.5 m B.G.L.), 8.1 m above the level of the uncontrolled discharge. Upon commencement of pumping, the water level in the borehole dropped very rapidly to 175.2 m A.O.D. (19.8 m B.G.L.). Water level data logging began from this point. Figure 2 illustrates the drop in water level over time, in relation to the pumping rate. It can be seen that drawdown was initially rapid. However, the rate slowed after three days, from which point an almost constant rate of drawdown was evident. Sudden increases in water level in the borehole were predominantly a consequence of periodic pump failures, though these demonstrate that borehole water level rose rapidly when abstraction ceased.

At Llanhilleth, some 6 km down the valley from the Vivian shaft at Six Bells colliery, mine water is confined below the surface. Following closure of the Llanhilleth workings in the 1960s, water was pumped to Six Bells, and therefore it was known that a connection between the two existed at one time. A borehole was driven into the abandoned Llanhilleth mineworkings, to allow water level measurement. As it turned out, artesian conditions were encountered, and therefore a pressure gauge was installed at the surface. When the

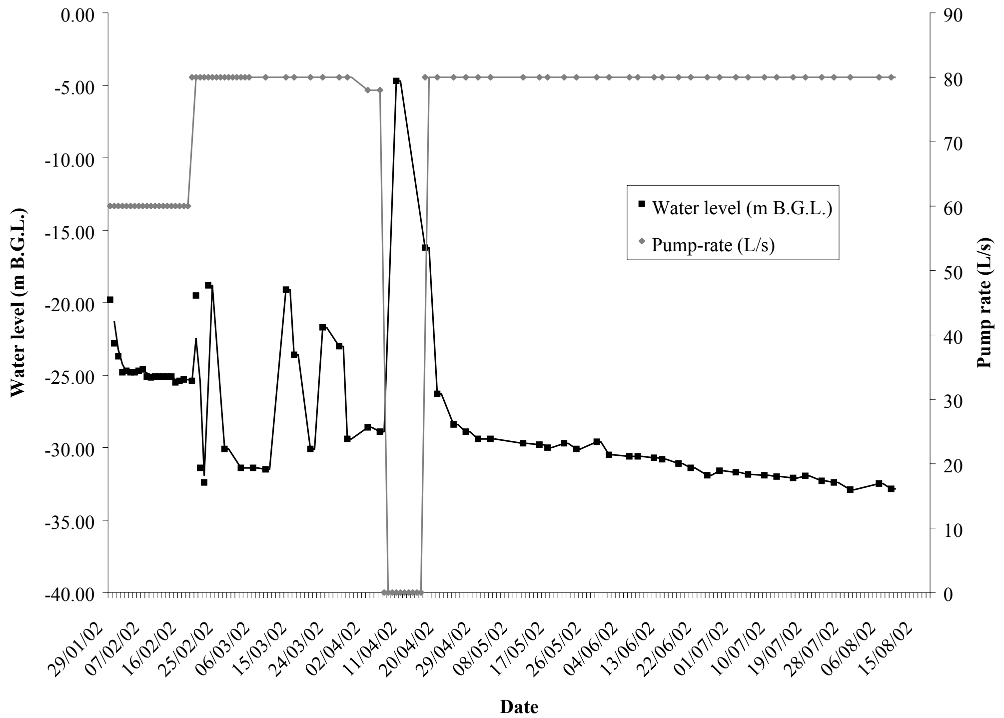

Figure 2. Borehole abstraction rate and borehole water level at Six Bells

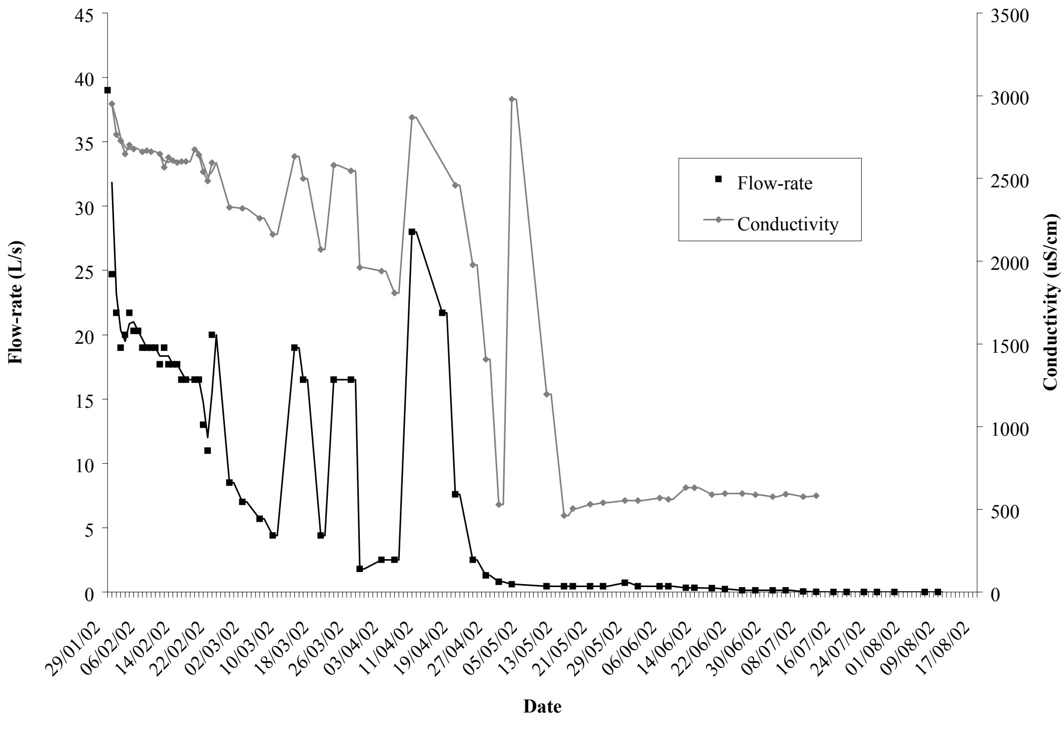

Figure 3. Relationship between uncontrolled discharge flow-rate and discharge conductivity.

water level in the borehole at Six Bells reached 25.60 m BGL, monitoring of the water pressure gauge at the Llanhilleth shaft demonstrated that abstraction at Six Bells was indeed reducing the water pressure at Llanhilleth. Therefore, pumping at Six Bells was clearly influencing an extensive area of abandoned workings.

The lowering water level in the borehole was matched by a gradual decrease in the volume of the uncontrolled discharge, as illustrated in Figure 3. Also shown on Figure 3 is the conductivity of the uncontrolled discharge. The relationship between discharge flow-rate and conductivity is striking; there is a positive correlation between the two variables (correlation coefficient, $r = 0.85$; $p < 0.001$). Similarly, comparing the water level in the borehole (Figure 2) and the flow-rate of the uncontrolled discharge (Figure 3), a relationship is apparent ($r = 0.82$; $p < 0.001$). A direct connection existed between the roadway intercepted by the borehole and the conduit from which the uncontrolled discharge emanated. The reason for the improvement in quality of the uncontrolled discharge, represented by decreasing conductivity, is less clear. One possibility is that the influence of deep mine water gradually reduced, to a point where latterly the discharge was entirely comprised of a temporary source of surface water (represented, in Figure 3, by the sudden drop in conductivity to around 500 μS/cm), subsequently removed by continued pumping.

The preceding discussion serves to illustrate the complex hydrological and hydrochemical interactions occurring within the abandoned mine workings at Six Bells. Predicting hydrological/hydrochemical changes during abstraction is highly difficult, which only reinforces the logic of undertaking a pump test prior to finalising a treatment scheme. The paradox at Six Bells was that, in order to discharge water of an acceptable quality during the pump test, the treatment scheme had to be constructed *before* the pump test commenced. The remainder of this article discusses the treatment of the abstracted water, which varied both in quantity and quality.

WATER TREATMENT

The treatment system for the Vivian shaft discharge (Six Bells colliery) was designed to treat a net-alkaline water, flow-rate ≤60 L/s, with approximately 40 mg/L iron. This was to be facilitated using hydrogen peroxide dosing, followed by settlement. However, the actual water quality was initially quite different: a net-acidic water with in excess of 200 mg/L iron, at a flow-rate of 80 L/s. Two issues combined to preclude the use of hydrogen peroxide under these circumstances:

1. Treatment of a net-acidic water using hydrogen peroxide would have done nothing to counteract the acidity of the water. Indeed, potentially a drop in pH would have been seen across the settlement ponds, since hydrolysis of ferric iron is a proton-generating reaction:

   $$Fe^{3+} + 3\,H_2O \rightarrow Fe(OH)_3 + 3\,H^+$$

2. The system was incapable of providing a large enough hydrogen peroxide dose to meet the demand of the higher flow-rate and iron concentration.

The discharge quality imposed by the Environment Agency was that the discharge from the treatment system should not result in an increase in total iron load to the river (above that imparted by the uncontrolled discharge). With this in mind, an alternative treatment strategy had to be adopted until such time as the quality of abstracted water improved.

As part of a previous mine water treatment scheme, a mobile chemical dosing plant, for addition of caustic soda (NaOH), had been constructed on behalf of the Coal Authority. Therefore the temporary solution to the treatment of the Vivian shaft water was to dose with caustic soda in order to raise to pH >8.5, and precipitate iron as the ferrous hydroxide ($Fe(OH)_2$). Although an unusual approach to the removal of iron (which is more typically removed as the ferric precipitate), previous experience at Frances colliery, Fife, Scotland, had shown that this was feasible.

Initially, a 20% NaOH solution was used, to prevent freezing problems. This was subsequently replaced with a 32% solution, to reduce the number of deliveries required and avoid the need to replace the dose pump with one with a greater capacity. The NaOH dose rate varied between 200 L/hr and 400 L/hr during the early part of the pump test, reflecting varying water quality and quantity. During the constant rate test dose rate was 325 L/hr. Once the iron concentration had dropped to less than 150 mg/L, dosing with hydrogen peroxide, using the permanent installation at the site, commenced. The rate of hydrogen peroxide dosing has remained constant, at 22 L/hr. Figure 4 illustrates the substantial removal of iron, both with the use of NaOH and H_2O_2. On average, nearly 95% of the total iron load is removed following chemical dosing and settlement. Mean effluent iron concentration was just 5.4 mg/L, and the maximum recorded was 27 mg/L.

At the time of writing the tertiary treatment wetland is being commissioned. This will effect further improvements in effluent water quality, and the long-term objective is to discharge water with an iron concentration of less than 2 mg/L.

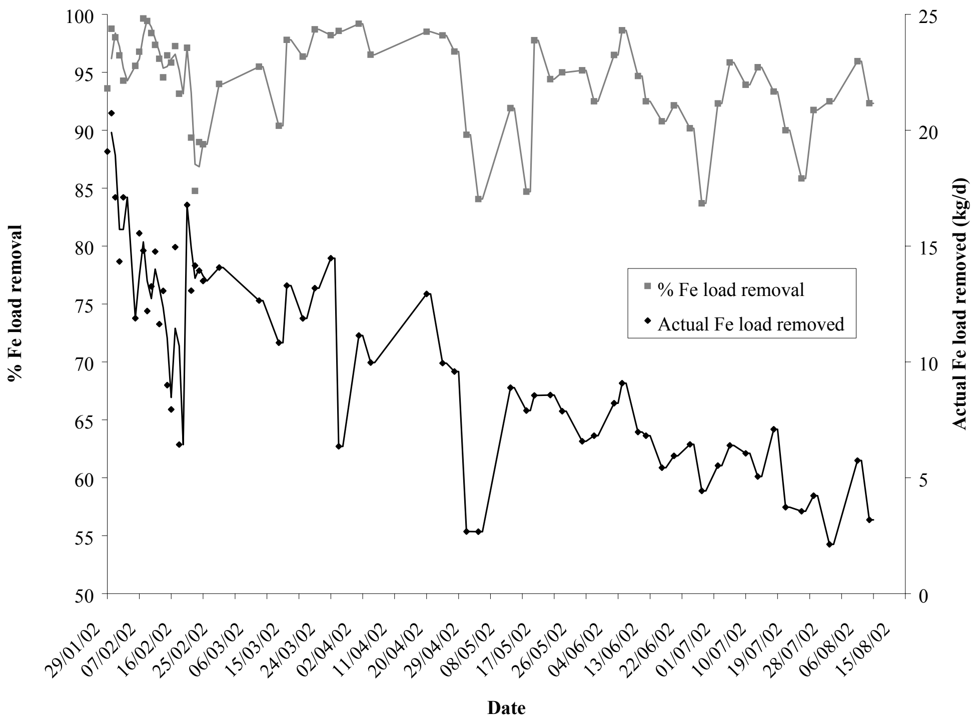

Figure 4. Performance of chemical dosing and settlement at Six Bells, in terms of iron load removal.

DISCUSSION

Following completion of the scheme, the subsequent pump test produced net-acidic water with a very high iron concentration, and it was determined that dosing with hydrogen peroxide alone (as designed) would not be sufficient to meet required effluent water quality standards. Therefore caustic soda was used during the first month of the pump test, when water quality was at its worst. Caustic soda was dosed using a dedicated mobile plant, which was removed from the site once the worst quality water (the 'first flush') had been treated (after approximately 1 month). Subsequent treatment using hydrogen peroxide has proved highly successful, with iron concentrations falling well within regulatory limits. A tertiary treatment wetland, just commissioned at the time of writing, will further reduce iron concentrations.

At the time of writing, the borehole pump rate is being gradually reduced, with a view to optimising treatment. Ultimately it is hoped that the pump rate can be reduced to that of the original uncontrolled discharge, though it is unclear how long it will take to reach this equilibrium condition.

As the pump test commenced, a falling trend of iron concentration was noted, reminiscent of the 'first flush' phenomenon of uncontrolled gravity discharges (Younger 1997). Also, as the water level in the borehole fell, the flow-rate of the uncontrolled discharge decreased, proving the hydraulic connection between the two. As the uncontrolled discharge flow-rate decreased, conductivity also dropped, possibly indicating a gradual decrease in the contribution of polluted mine water to the uncontrolled discharge.

The key lesson learned from the experience at Six Bells is that it is always advisable to build flexibility into the design of treatment systems. Specifically, when mine water is intercepted before emerging at the surface by gravity, its quality is invariably unknown. In such situations, passive treatment alone may not be adequate for successful treatment. Because of the risks associated with allowing mine waters to rise in an uncontrolled manner, several major treatment initiatives are currently underway in the UK that involve pumping water to the surface from deep mine workings. In these cases, it is advisable to build into the design facilities for temporary active treatment, even if the long-term plan is for passive-only treatment. This is particularly the case at sites like Six Bells, where regulatory conditions dictated that the treatment system was built before the pump test was undertaken (similar situations are now arising at other sites in the UK). However, it is advisable to build flexibility into all mine water treatment systems, even for uncontrolled discharges wherever reasonably practicable, since the quality of long-running discharges has also been known to change e.g. Bullhouse and Sheephouse mine waters, Yorkshire. Items that add flexibility to a scheme may include:

- an area of hard standing for positioning dosing apparatus;
- a power source;
- water supply (for decontamination purposes);
- pipework for attaching dosing lines;
- drainage for potential spillage;
- readily accessible sampling points;
- access for tanker deliveries.

Provision of such additional items can allow for treatment of poor quality 'first flush' water during the early period of treatment, or indeed subsequent changes in water quality, at relatively low cost. Such flexibility is not feasible in passive-only treatment systems, without significant over-design, and the result may be severe contamination of receiving watercourses. The provision of temporary active treatment facilities, and the treatment performance possible with them, is being built into new design guidelines for mine water treatment schemes (e.g. Laine and Jarvis 2002).

CONCLUSIONS

A treatment scheme has successfully been constructed to remediate mine water pollution of the Ebbw Fach river, South Wales. Interception of the water was facilitated by the installation of a 216 m deep borehole, which intercepts a roadway junction within the abandoned workings.

Circumstances dictated that the mine water treatment scheme had to be constructed before a pump test was undertaken. Although there was a precedent for suspecting that pumped water quality might be worse than that of the uncontrolled discharge, the treatment system was nevertheless based on the uncontrolled discharge (albeit under worst case conditions). To do otherwise was unrealistic for two reasons:

1. prior to the commencement of the pump test there was no way of confidently knowing the quality of the water that would be abstracted;
2. even if the pumped water quality had been known, the capital expenditure for a scheme designed on the basis of the worst quality pumped water would have been significantly greater than that of a scheme based on the uncontrolled discharge. In the long term, improvements in pumped water quality would have rendered such a system over-sized.

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