# Developments and Challenges in the Management of Mining Wastes and Waters in Europe

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## ABSTRACT

European Union legislation strongly influences approaches to mine waste / water management in Europe. However, because Europe-wide legislation is subject to national-level transposition and implementation, the overall picture of mine waste / water management in Europe is complex. There are nevertheless some research and development themes that are common across Europe. These include efforts to improve characterisation and prediction of drainage, the development of small-footprint passive treatment systems, and the development of approaches for compiling risk-based inventories of mine wastes at a national scale. In addition, there is an increasing emphasis on identifying more sustainable approaches to mine waste and water management, such as the use of waste products for remediation, and the recovery of valuable metals from abandoned mine waste streams. There is also a collective concern to understand, and therefore avoid in the future, catastrophic tailings dam failures, such as that at the Ajka bauxite residue depository in Hungary in October 2010.

The Partnership for Acid Drainage Remediation in Europe (PADRE) is endeavouring to ensure that professionals developing solutions to mining pollution are aware of the complimentary work of others across Europe, and that internationally significant work conducted in Europe is effectively rolled out to a global audience.

## 1. INTRODUCTION

Europe has a long and rich history of mining, but there are now significantly more abandoned mines than operational mines across the continent. Consequently, considerable attention is focused on addressing the environmental legacy problems associated with these orphan sites. Key legislative instruments which are influential in driving environmental improvements are the European Union (EU) Water Framework Directive (2000/60/EC) and EU Directive on the Management of Waste from the Extractive Industries (2006/21/EC). These two major pieces of legislation are subject to transposition into national regulations across individual states of the European Union, and are therefore subject to slight differences in application between nations. Nevertheless, the underlying principles apply across all European Union member states.

The extent to which individual member states of the European Union have progressed with addressing the environmental pollution associated with (abandoned) mine sites is variable, as are the particular priorities in different countries, which are in part driven by differences in the specific historic mining activity and the environments potentially impacted. The scientific and engineering approaches to overcoming mining pollution problems also vary. Thus, research and development activities across Europe are wide-ranging.

PADRE is the Partnership for Acid Drainage Remediation in Europe. One of PADRE's main ambitions is to attempt to act as a repository for capturing this wide variety of R&D activity, and also to ensure researchers, consultants and mining industry personnel are both aware of the historic and current outputs of this R&D, but also avoid replication of effort, and are able to quickly identify potential collaborators. The specific objectives of PADRE are (as stated in the PADRE Statutes):

a. To provide a network and collaborative platform for European and international research and development into techniques for the prediction, prevention and remediation of acidic drainage in Europe.
b. To promote dissemination of knowledge of current best-practice and innovations relating to acidic drainage prediction, prevention and remediation, with particular reference to European conditions, including the evolving framework of relevant EU legislation.
c. To advance the training of present and future generations of European professionals who will engage in the art and science of acidic drainage prediction, prevention and remediation.
d. To actively collaborate with a Global Alliance of organisations based in other continents which share similar objectives.

In this paper we provide a review of both the environmental problems faced by Europe due to current, and especially historic, mining activities, and also some examples of the R&D activities that are currently being pursued across Europe. It is PADRE's ambition that a far more detailed coverage of R&D activities will become available on PADRE's website in the coming months and years, and the case studies presented in this paper aim to illustrate the type of information which it is hoped will become available on the website in due course (for many hundreds of investigations if possible).

## 2. MINE WATER ISSUES IN EUROPE: AN OVERVIEW

In 2004 and 2005 the International Mine Water Association, through its journal *Mine water and the Environment*, published reviews of mine water issues across Europe. The coverage of countries was not complete, but this is not to say that those countries for which mine water issues were not reviewed do not have problems; Spain being a good example. Notwithstanding some notable omissions, the review provided a useful indication of the scale and range of problems in Europe, which primarily relate to abandoned mine facilities. A summary of these reviews is provided in Table 1.

It is clear, even from the brief summary in Table 1, that groundwater and surface water pollution are major issues, irrespective of whether they occur due to rising waters in abandoned deep workings, or from waste rock piles and tailings facilities. It is little surprise therefore that a particular focus of R&D efforts across Europe has been the management of these wastes and waters. Some of the initiatives being pursued are discussed below as case studies of mine water R&D in Europe.

Although many of the problems facing Europe are chronic issues of long-term pollution, such problems have been brought into sharp focus by catastrophic events at mining facilities. Notable amongst these are the release of around 50 000 $m^3$ of strongly acidic, metal-rich, mine water from the abandoned Wheal Jane tin mine, Cornwall, UK, in January 1992, and the infamous tailings dams failures at Aznalcóllar, south western Spain, in April 1998, and at Baia Mare in Romania, in January 2000. The tailings dams failures at Aznalcóllar and Baia Mare in part resulted in new legislation to guard against such incidents; the Seveso II Directive (2003/105/EC), which relates to prevention of spillages from chemical industries, was extended in the wake of the Baia Mare incident to cover risks arising from storage and processing activities in mining, and the Directive on the Management of Waste from the Extractive Industries (2006/21/EC), often referred to as the "Mining Waste Directive" (MWD) came into force in May 2006, partly in response to these incidents. Nevertheless, the catastrophic events at the Ajka Timfoldgyar Zrt alumina plant in Hungary, in October 2010, when a tailings dam collapse released some 600000 – 700000 $m^3$ of bauxite processing residue (red mud), are a tragic illustration that more can be done in this area.

Table 1. An overview of mining and mine water management issues in a selection of European countries (adapted from Jarvis and Wolkersdorfer, 2009)

| Country | Brief description of minerals exploited / status of mining | Environmental management concerns |
|---|---|---|
| Estonia[1] | Oil shales / ongoing | Groundwater depletion due to dewatering; elevated $SO_4^{2-}$ concentrations |
| Finland[2] | Metal sulphides, exploited esp. for Fe, Cu, and also Au | Surface water pollution from tailings; some groundwater pollution from tailings facilities |
| France[3] | Coal, Fe, U, F, K hydroxide, Au and Ag / largely abandoned | Contamination of surface / groundwater by mine water rebound; flooding and subsidence |
| Germany[4] | Coal, lignite, iron ore, fluorspar, salt, copper / all ongoing | Surface water contamination from tailings, waste rocks and mine voids; rising mine waters |
| Hungary[5] | Brown coal, Mn, bauxite / largely abandoned | Continued mine water pumping to protect groundwater supplies from products of pyrite oxidation and dissolution |
| Italy[6] | Various, but including Sn, Cu, Pb, Zn minerals, pyrite and lignite / largely abandoned | Pollution of surface and groundwater, due to rebound, with sulphate and metals. Subsidence / collapse. |
| Macedonia[7] | Pb, Zn, Fe, Cu, precious metals, industrial minerals, coal | Surface and groundwater pollution from active and abandoned mines, and land contamination |
| Netherlands[8] | Coal / largely abandoned | No serious issues as yet. Rising waters continue to be monitored, but believed to be hydrologically isolated from adjacent water supply aquifers |
| Norway[9] | Principally copper and sulphur / largely abandoned | Surface water contamination from tailings, waste rocks and mine voids |
| Poland[10] | Various, including coal, lignite, lead, zinc, copper / ongoing, but much reduced since 1989. | Groundwater and surface water contamination from tailings, waste rocks and mine voids; utilisation of pumped saline mine water |
| Serbia and Montenegro[11] | Non-ferrous and precious metals, bauxite, coal | Serious and wide-ranging water and land pollution issues, including pollution from both abandoned and operational facilities |
| Slovakia[12] | Au, Ag, Cu, Fe, polymetallic ores, coal, magnesite, gypsum / metal mining abandoned, coal, magnesite, gypsum ongoing. | Impacts on groundwater supplies and contamination of surface waters |
| Sweden[13] | Base metals, iron, gold | Principal concerns relate to mine wastes causing surface and groundwater pollution with metals |
| United Kingdom[14] | Coal, lead, zinc, copper, tin / largely abandoned | Surface water contamination; groundwater rebound leading to aquifer pollution; surface water contamination from waste rock dumps |

Sources: [1]Puura (2004), [2]Räisänen et al. (2005), [3]Blachère et al. (2005), [4]modified from Hasche and Wolkersdorfer (2005), [5]Sárváryné-Szentkatolany (2004), [6]Garzonia (2004), [7]Midžić and Silajdžić (2005a), [8]Miseré and Wings (2004), [9]Walder and Nilssen (2005), [10]Witkowski (2005), [11]Midžić and Silajdžić (2005b), [12]Bajtoš (2004), [13]Destouni (2005), [14]Jarvis and Rees (2004)

Although incidents such as those identified above are patently cause for very serious concern, and action to prevent such incidents happening in the future is essential, the problems of chronic pollution from abandoned mining facilities are arguably more damaging to the environment in the medium- to long-term.

For example, though the outburst from the Wheal Jane tin mine was a highly visible incident (causing the Fal estuary to turn bright orange), the environmental effects of the outburst itself were reportedly only relatively short-term (Somerfield *et al.*, 1994; Younger *et al.*, 2005). In contrast long-running, uncontrolled, discharges from abandoned metal mines across the former mining districts of England and Wales are a cause of significant long-term ecological degradation in surface waters (e.g. Armitage *et al.*, 2007). It is for that reason that the case studies briefly outlined below are focused on such long-term issues.

## 3. CASE STUDIES OF MINE WATER R&D IN EUROPE

Clearly it is not possible to provide an exhaustive review of all the R&D activity that has, and is, happening across Europe in a short paper such as this. The intention here is to provide just a few examples of the type of work that is being undertaken, in this case drawn from some of the direct experiences of these authors. The reason for doing so is to illustrate the breadth of research work that is being undertaken. We hope that in the coming months and years the PADRE website will become populated with similar case studies, covering a whole host of topics and sites, to the benefit of all those involved in the investigation and remediation of environmental challenges in the mining sector.

### 3.1 Waste characterisation: A case study from Hungary

The Rudabánya mine area is one of the oldest mining sites within the Carpathian region. Mining of different ore resources has taken place from the Neolithic Age (native copper), through the 14th–16th centuries (silver and copper) until the 1980s (carbonate iron ore). The deposit is located in the Lower Triassic transgressive series (fine-grained sandstone, clay marl, bituminous dolomite) that was disintegrated by polyphase folding and thrusting. The overlaying carbonate rocks are present in 10-100 m sized blocks embedded in the strongly folded gray clay marl. A 4-stage ore formation model was developed as: (1) siderite and hematite formation in the Bódvaszilas sandstone, (2) metasomatic sideritization of the Gutenstein dolomite, (3) formation of the baritic border zone with Cu- and Pb sulphides on the borders of the siderite bodies, (4) late epithermal formation of sulphosalts accompanied by pyrite (Pantó, 1956).

New exploration works during the 1990s suggested a Mississippi Valley-type (MVT) massive sulphide mineralization of Pb and Zn. Recent explorations (Földessy et al. 2009) focused on base metal enrichments that occur not only in the baritic border zone but also on stratabound lenses in the clay marl, siltstone and fine-grained sandstone. Significant Zn-content was detected in cryptocrystalline sphalerite lenses and, less commonly, in smithsonite cancretions.

Despite the fact that carbonates dominate the host rock, and that iron sulphides have comparatively limited abundance, it was nevertheless considered worthwhile evaluating the Rudabánya site with respect to possible Metal Leaching / Acid Rock Drainage (ML/ARD) formation. An important factor in this instance is the large quantity of iron-rich carbonates among the potential waste rocks. If the siderite-content is more than 20% of the carbonates present then the acid neutralizing potential measured by the standard ANC test (Sobek et al., 1978) will fall far below the NP values predicted by carbonate-content.

The aim of the work was therefore to check the acid generating potential of some sulphide-rich site rock samples from the exploration project, taking into account the significant iron-content of the host carbonate minerals. An important additional aim was to evaluate the applicability of the new European standard on mine waste characterisation. The need for this standard has arisen from the EU Mining Waste Directive, and the new standard will form the primary guidance for characterisation of mining waste, especially its acid generating potential. The specific aspect of the new standard that was examined in this work was the applicability of the new standard in circumstances where comparatively slow-reacting carbonates, and especially iron-bearing carbonate phases, are present.

For this work 7 samples were selected from the ore type collected during the exploration project. All selected samples represent different ore / site rock types with different sulphide composition. The general characteristics of these ores are shown in Table 2. The more general mineralogy of the samples is summarised in Table 3.

Table 2. Characteristics of the ore samples collected in terms of carbonate content and sulphide content

| **Sample ID** | **description** | **% $CaCO_3$ (ISO 10693)** | **Total S % (ISO 351)** | **Pyrite S %** | **Sulphide S %** | **Sulphate S %** |
|---|---|---|---|---|---|---|
| A | Sample from mine waste dump. Intensively cemented breccia of oxidized sparry iron ore (goethite 9%). | 0.81 | 2.23 | 1.83 | 1.83 | 0.40 |
| B | Gray, slaty, brecciated clay-marl. Zn- and Pb-bearing sample from contact zone of marl and carbonate ores | 27.86 | 5.92 | 2.00 | 5.47 | 0.45 |
| C | Dolomitic pyrite-rich sparry iron ore close to contact zone with the marl | 43.81 | 6.1 | 6.10 | 6.10 | 0.00 |
| D | Dolomite-rich sparry iron ore with vein-filling fahlore and pyrite | 66.10 | 2.806 | 2.14 | 2.81 | 0.00 |
| E | Pyrite-rich sparry iron ore | 51.73 | 13.21 | 13.06 | 13.06 | 0.15 |
| F | Massive pyrite accummulation in sparry iron ore | 13.15 | 30.83 | 29.72 | 29.72 | 1.11 |
| G | Sample from the "baritic spare edges" with significant barite and pyrite content | 0.38 | 15.38 | 6.09 | 8.45 | 6.93 |

Table 3. Mineral composition (wt%) of samples from X-Ray Powder Diffraction (XRPD) analysis

| **Sample No.** | **A** | **B** | **C** | **D** | **E** | **F** | **G** |
|---|---|---|---|---|---|---|---|
| Mg-siderite | 66 | | 8 | 2 | 5 | | |
| Dolomite | 4 | 26 | 52 | 74 | 36 | 23 | 9 |
| Dolomite Fe-rich | 2 | 11 | 19 | 15 | 27 | | |
| Magnesite | | | 7 | 3 | | | |
| Calcite | | | | | 1 | | |
| Cerussite | | 1 | | | | | |
| Covellite | | 5 | | | | | |
| Pyrite | 8 | 5 | 14 | 3 | 30 | 66 | 11 |
| Sphalerite | | 9 | | | | | |
| Tetrahedrite | | | | 2 | | | |
| Galena | | | | | | | 17 |
| Gypsum | 5 | 2 | | | 1 | 7 | 2 |
| Anhydrite | | 1 | | | | | |
| Barite | | | | | | | 46 |

The results of the series of experiments are shown in Table 4, and graphically in Figure 1. The static batch tests showed that, as expected, samples with very high pyrite content (F) or with high pyrite content and very low carbonate (G) were acid generating. Interestingly, the 30 second pH stability at the end of the Acid Base Accounting (ABA) test was not reached for the carbonate-rich samples. In fact the slowly-reacting carbonates (dolomite, Mg-siderite) continued to react for a further 10–12 hours.

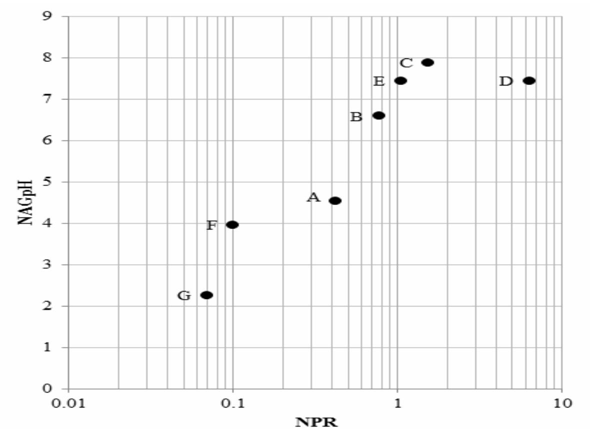

Figure 1. Graphical illustration of results, showing the strong acid-generating potential of the pyrite-rich / Carbonate poor samples.

The results suggest that acid addition, and the closing phase of the Neutralisation Potential (NP) determination, should be further elaborated in the draft EU standard on mine waste characterisation. Specifically, the results of these experiments suggest that correction for slowly-reacting carbonate phases may be required, or additional measures should be included to account for such mineralogy. More generally the results illustrate that whilst standardised guidance for such tests is clearly beneficial, there is a clear need to have the necessary expertise to interpret results appropriately, and in particular recognise circumstances in which the strict adherence to the guidance may not illuminate all aspects of the potential for acid generation / neutralisation potential of a particular mine waste.

Table 4. Results of static batch tests

| Sample ID | NAG pH | NP (kg $CaCO_3$/t) | AP (kg $CaCO_3$/t) | NPR | NNP (kg $CaCO_3$/t) |
|---|---|---|---|---|---|
| A | 4.54 | 29.57 | 69.69 | 0.42 | -40.11 |
| B | 6.59 | 143.63 | 185.00 | 0.78 | -41.37 |
| C | 7.88 | 292.95 | 190.63 | 1.54 | 102.33 |
| D | 7.45 | 556.22 | 87.69 | 6.34 | 468.53 |
| E | 7.45 | 436.41 | 412.81 | 1.06 | 23.59 |
| F | 3.95 | 100.87 | 963.44 | 0.10 | -862.56 |
| G | 2.26 | 18.93 | 263.75 | 0.07 | -244.82 |

### 3.2 Surface water impacts: A case study from Spain

One of the most important mercury mining districts in Spain is located in Asturias, in the north-west of the country. In the Mieres and Pola de Lena districts, both in central Asturias, and within the Caudal River catchment, important mines were exploited from pre-Roman to the 1970s, when they were abandoned. The environmental legacies of these historical Hg mining activities are evident as abandoned underground mines and waste rock piles which constitute potential sources of environmental pollution of both soils and waters.

The most important mines exploited in this area were La Soterraña and La Peña El Terronal. At La Soterraña mine site a small tributary of the Caudal River flows through the area, collecting surface runoff, mine water and spoil heap leachates. The impact of this abandoned mine on the water environment is mainly evidenced by the presence of high levels of As downstream of the mine operations, with As concentrations up to 57 mg/L, as a consequence of the weathering of As-rich wastes and ore. Dissolved Hg concentration was always below 0.5 µg/L. At La Peña-El Terronal mine site, As concentrations up to 6.7 mg/L have been measured downstream of the mine workings, whilst Hg concentration was always below 0.5 µg/L. In the Caudal River, the receptor of the streams and rivers flowing through the mined areas, As concentrations show values below the detection limit (0.03 mg/L), with the exception of a sampling point located downstream of La Soterraña mine, which reached a concentration of 0.09 mg/L.

Mass loadings of As have been calculated using flow and concentration data from locations both upstream and downstream of the mines. The concentrations were always < 0.10 mg/L upstream of both sites, whereas average concentrations of 49 and 4.6 mg/L were found downstream of La Soterraña and La Peña - El Terronal mine sites respectively. Mean flows of the watercourses downstream of the mine sites were 0.32 L/s and 53 L/s respectively. Therefore, the calculated As loads that these streams carry to the Caudal River are 1.3 kg/d and 19.7 kg/d for La Soterraña and La Peña-El Terronal mine sites respectively, as a mean over the monitoring period. This constitutes a considerable input to Caudal River catchment, even when As is undetectable in the Caudal River itself due to its high flow. At least some proportion of the As is likely retained in the bed sediments of the Caudal, which itself may have implications for chemical and ecological quality of the river.

It should be noted that the main As input comes from El Terronal site. Groundwater sampled in wells near the mine sites, used for irrigation and as drinking supply for animals, show As concentrations ranging from 1.2 – 15 µg/L. The mine site with the current highest input to the Caudal River catchment (La Peña-El Terronal) is the only one in which a remediation plan, consisting of the encapsulation of the main waste rock pile, has been implemented. Figure 2 shows different stages of the construction of the remediation, in which the mine and metallurgical wastes have been encapsulated (Figure 2A), and a highway has been constructed over the encapsulated waste (Figure 2B).


Figure 2. Mine waste encapsulation at El Terronal Hg mine (A), and road construction over encapsulated mine waste (B)

This case study illustrates the importance of measurements of mass flux (mass per unit time) of metal contaminants from mines sites, not just metal concentrations, to make a proper evaluation of possible environmental impacts. As an illustration of the importance of mass flux, Mayes *et al.* (2009) recently concluded, on the basis of metal *concentration* data, that 6% of all the river catchments in England and Wales were adversely affected by discharges from abandoned metal mines. However, although 6% is a significant proportion in its own right, in subsequent work Mayes *et al.* (2010) went on to show that in terms of metal *flux*, metal mines alone are responsible for contributing at least 50% of all the Zn in freshwaters of England and Wales (with the other 50% due to all other sources combined). Thus, the measurement of metal flux showed the true extent and severity of pollution from abandoned metal mines in England and Wales.

### 3.3 Prevention of ARD using waste from other industries: A review from Sweden

Sealing layers are usually constructed by using a natural soil which, in Sweden, is generally clayey till. The function of such conventional soil covers is reasonably well understood (e.g. Höglund *et al.,* 2004; GARD Guide: www.gardguide.com). In recent years, research has been performed to find a use for by-products such as sewage sludge, fly ash and green liquor dregs (GLD) to prevent or treat acid mine drainage and take advantage of the reactive nature of these materials. Using industrial waste would solve two waste problems at the same time, whilst simultaneously reducing reliance on virgin materials. However, the function of the alternative materials must be studied in detail before they can be used on an industrial scale. In particular, reliable predictions of the long-term efficiency are important.

GLD have a low hydraulic conductivity and are alkaline (pH 11-13; Nurmesniemi *et al.*, 2005; Maurice *et al.*, 2009; Hargelius, 2008), which makes it a potentially promising material for use in construction of sealing layers. GLD mixed with fly ash and bark sludge was found to be an efficient way to reduce the release of metals in tailings by Maurice *et al.* (2010), for example.

Fly ash alone, or mixed with sewage sludge, is also a material with potential for use in the remediation of tailings, both in cover applications and for stabilization / solidification applications. Bäckström and Karlsson (2006) showed that a cover made of a mixture of ash and digested sewage sludge reduced metal leaching from tailings, and furthermore that a vegetation cover could be successfully established.

The use of sewage sludge in sulphide mine waste remediation largely occurs by surface application to promote a suitable organic substrate for plant establishment (Neuschütz and Greger, 2008). Large-scale applications of sewage sludge have been investigated extensively in Sweden. Applications have been made to promote vegetation establishment on waste rock facilities, such as at the Aitik copper mine in northern Sweden (Forsberg *et al.*, 2008), and on the Gillervattnet tailings impoundment at Boliden, also in northern Sweden (Neuschütz and Greger, 2008). However, the success of establishing vegetation for acid prevention has often been hindered by diffusion of oxygen through the uncompacted sewage sludge layer and through root penetration, causing sulphide oxidation in the underlying waste.

Nevertheless, sewage sludge has been proposed for use as a suitable barrier material for a sealing layer (Mácsik *et al.*, 2003) due to its impermeable characteristics upon compaction, which prevents the diffusion of oxygen to underlying mine waste. The use of sewage sludge as a sealing layer is prohibited in Sweden due to the possible release of constituents such as readily leachable trace elements (Al, Mn, Cu, Ni, Zn; Stehouwer *et al.*, 2006) and nitrate concentrations which exceed EU and Swedish EPA limits (Eriksson, 2001). Also a reduction of the cover integrity over time has been identified (Ahlberg, 2006) due to the oxidation and degradation of organic matter in the barrier material.

This Swedish case study is just one example of efforts to use one industrial waste to alleviate environmental problems arising from mining waste. There is a clear logic in endeavoring to do so, though it to expand the portfolio of options available, and particularly to implement full-scale schemes at mining sites, will necessitate the agreement of the appropriate regulatory authorities.

### 3.4. Potential environmental problems from abandoned mines: Case Study from Germany

Like many other European countries, Germany has a long mining tradition, and there are several thousand abandoned mines in the former German mining regions. Currently, however, there is no comprehensive mine water inventory, and the impact of potentially toxic mine drainage on the aquatic environment cannot be reliably estimated. An unofficial list comprises 125 drainage adits, which together discharge ≈ 90 000 000 $m^3$ of polluted mine water annually. However, this list includes only those adits where problems were encountered in the past, and therefore has been compiled on an *ad hoc* basis. There has still not been a systematic survey of existing mines with coverage of all the former German mining districts.

In order to get a more accurate impression of the scale of problems related to abandoned mines in Germany, a relatively small Bavarian mining district was chosen (Figure 3) and all known mine adits were sampled. In this southern part of Bavaria, several dozen underground pitch coal mines were mined on an industrial scale between the 19th and the 20th century, albeit reports suggest that locally coal mining may date back as far as the 16th century. In 1960, due to political and economic circumstances, the Bavarian Government and the mine operators decided to close down the remaining mining operations. Consequently, the last Bavarian pitch coal mine at the Hohenpeißenberg closed in 1971.

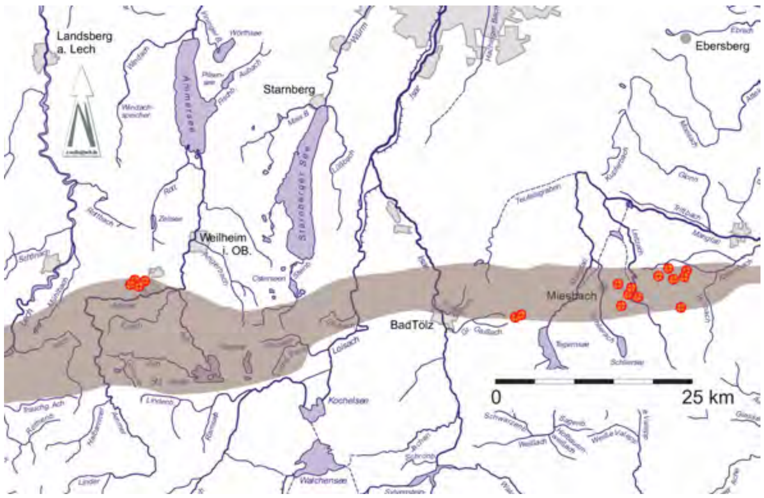


Figure 3. Location of the Southern Bavarian coal mining district south of Munich. Main locations: circles with red and orange crosses; the main syncline hosting the coal deposits is shaded.

A total of 17 mine water samples were collected and analysed in 2008. Electrical conductivities of the mine waters range between 407 and 4884 µS/cm with a mean of 1458 µS/cm and therefore significantly exceed the maximum electrical conductivity of 207 µS/cm reported for the hydrogeological subunit (Faltenmolasse) in which the mines occur. Also the temperature is slightly elevated (mean of 9.9 °C compared to 8.4 °C). Although pH values show little deviation from the normal hydrogeological situation (7.50 compared to 7.45), the data nevertheless indicate that these mine waters are chemically distinct to the normal hydrogeological situation in the subunit.

Ten of the waters sampled are normal alkaline earth waters, of predominantly bicarbonate composition (Furtak & Langguth classification), five are alkaline earth waters with higher alkali concentrations with elevated sulphide content, one is a normal earth alkaline water of bicarbonate-sulphide compostion, and another one is an earth alkaline water with a higher alkali content and of predominantly bicarbonate composition. All the mine waters falling into the predominantly sulphidic category are also characterized by electrical conductivities above 2 mS/cm and elevated trace element contents. Those waters, emanating from the Marienstein pile, Peißenberg Mittelstollen, Peißenberg Tiefstollen, Wasserstollen, and Ventilatorstollen can therefore be described as classical mine waters. Concentrations of trace elements reach up to: As 23 µg/L, Cr 6 µg/L, Ni 23 µg/L, Cu 5 µg/L, and Co 8 µg/L.

pH values range between 6.7 (Ventilatorstollen) and 8.3 (Marienstein pile). While the pH of the Ventilatorstollen is clearly influenced by pyrite oxidation, the Marienstein pile shows an influence from basic processing chemicals. All other pH-values range between 7.1 and 8.3, thus being well buffered in the bicarbonate buffer range, which might be expected from the local geological situation.

During the field investigation, which took place through the spring and summer seasons, the flows from the dewatering adits ranged between 1 and 2100 L/min with a mean of 180 L/min. The largest flow is that of the Ventilatorstollen, discharging into the river Leitzach. This discharge also has the highest electrical conductivity, sulphate, arsenic, cadmium, and iron concentrations. Its annual load is 14 t of Fe, 26 kg of As, 14 kg of Ni, 4 kg of Cu and approximately 1 kg of the aforementioned trace elements.

During the field investigation local reports were received of “red” water near the abandoned Achthal shaft. This shaft’s pit head has an elevation of about 550 masl (meters above sea level) and is connected to the Auer dewatering adit, which discharges 1.7 km to the North-East at an elevation of 510 masl. At both locations the mine water had a noticeable $H_2S$ smell and a low redox potential (110–250 mV). Since the mine water discharges at both the pit head of the Achthal shaft and at the Auer dewatering adit, between which there is a 40 m elevation difference, it appears that there is a partial blockage within the mine workings between the two. Should the pressure behind the blockage further increase, or the blockage becomes weaker, an outburst at the Auer dewatering adit, with an ensuing pollution of the receiving stream, may be a possibility.

In addition to the specific example of the potential for sudden outbursts, above, many of the discharges cause visible staining of the receiving streams, and in the case of the Ventilatorstollen adit reports have been made of fish kills following an outburst from the. Therefore, local authorities should ensure that the mine waters are treated accordingly, if possible with low-cost passive treatment systems (e.g. settling ponds with constructed aerobic wetlands), which would be more in keeping with the local landscape of Upper Bavaria.

More generally the substantial volumes of water, and elevated metal concentrations, of the discharges discussed here suggest that a systematic survey of the absolute flux of metals from abandoned mines across the *whole of Germany* would perhaps reveal that abandoned mine discharges have a significant role to play in absolute mass transfer of metals from terrestrial to aquatic environments nationally, in much the same way as Mayes *et al.* (2009, 2010) have illustrated this point for the UK abandoned mine situation.

## 4. Conclusions

The Partnership for Acid Drainage Remediation in Europe (PADRE) is attempting to develop a collaborative platform for European and international research and development into techniques for the prediction, prevention and remediation of acidic drainage in Europe, and improve the level of dissemination of information across Europe and internationally. The four contrasting case studies presented in this paper are examples of the type of information which PADRE aspires to make available to researchers, regulators and mining companies across Europe, principally via the new website of PADRE (www.PADRE.IMWA.info), exactly to promote improved collaboration and dissemination of R&D activities in ARD and related areas.

## References


Ahlberg, G. (2006) *Ageing of Sewage Sludge – some physical and chemical properties in relation to landscaping.* Unpublished PhD thesis, Department of Earth Sciences Geology, Göteborg University, Göteborg. Doctoral Thesis: 20.

Armitage, P.D., Bowes, M.J. and Vincent, H.M. (2007) Long-term changes in macroinvertebrate communities of a heavy metal polluted stream: the River Nent (Cumbria, UK) after 28 years. *River Research and Applications*, **23**, 997-1015.

Bäckström, M. and Karlsson, U. (2006) *Ash and sludge covering of mine waste*. Final report. Värmeforsk report 960, Februrary 2006 (in Swedish).

Bajtoš, P. (2004) Mine water issues in Slovakia. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 170-173.

Blachère, A., Morel, S. and Lefort, D. (2005) France. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 16-18.

Destouni, G. (2005) Sweden. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 7-10.

Eriksson, J. (2001) *Concentrations of 61 trace elements in sewage sludge, farmyard manure, mineral fertiliser, precipitation and in soil and crops*. Uppsala, Swedish University of Agricultural Sciences: 69.

Földessy, J., Németh, N., Gerges, A., Kupi, L. and Tóth, Sz. (2009): *Re-discovery of a mining district – the Rudabánya (Hungary) base metal mineralization*. 8th ICARD, June 22-26, 2009, Skelleftea, Sweden.

Forsberg, L. S., J. P. Gustafsson et al. (2008) Leaching of metals from oxidising sulphide mine tailings with and without sewage sludge application. *Water Air and Soil Pollution*, **194**, 331-341.

Garzonio, C.A. (2004) Italy – some examples of mine water problems in Tuscany. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 177-179.

Hasche, A. and Wolkersdorfer, Ch. (2005) Germany. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 10-13.

Hargelius, K. (2008) *Pilot scale experiment with sealing layer at the Ätran landfill, Field trial-Värö-FAVRAB-Hylte. Ramböll Sverige AB, Region Väst, Gothenburg*. Technical report (in Swedish).

Höglund, L-O, Herbert, R., Lövgren, L., Öhlander, B., Neretniks, I., Moreno, L., Malmström, M., Elander, P., Lindvall, M. and Lindström, B. (2004) *MiMi - Performance assessment*. Main report. MiMi-report 2003:3. ISSN 1403-9478, ISBN 91-89350-27-8.

Jarvis, A.P. and Rees, B. (2004) Mine water issues in the United Kingdom. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 164-165.

Jarvis, A.P. and Wolkersdorfer, Ch. (2009) Acid and metalliferous drainage remediation: legislative drivers, and research and development activities in Europe. *Proceedings of the 8$^{th}$ International Conference on Acid Rock Drainage*, Skellefteå, Sweden, 22-26 June 2009.

Mácsik, J., Y. Rogbeck, et al. (2003) *Fly ash and sewage sludge as liner material - Preparation for a pilot test with fly-ash stabilized sewage sludge as landfill liner*. Report 837. (In Swedish). Värmeforsk, Stockholm, Sweden.

Mayes, W.M., Johnston, D., Potter, H.A.B. and Jarvis, A.P. (2009) A national strategy for identification, prioritization and management of pollution from abandoned non-coal mine sites in England and Wales. I. Methodology development and initial results. *Science of the Total Environment*, **407**, 5435-5447.

Mayes, W.M., Potter, H.A.B. and Jarvis, A.P. (2010) Inventory of aquatic contaminant flux arising from historical metal mining in England and Wales. *Science of the Total Environment*, **408**, 3576-3583.

Maurice, C., Villain, L. and Hargelius, K. (2009) Green liquor dregs for the remediation of abandoned mine tailings- opportunities and limitations. *Proceedings of Securing the Future: Mining, metals* *and the environment in a sustainable society, and 8th ICARD, International Conference on Acid Rock Drainage*. 6 p.

Maurice, C., Mäkitalo, M., Villain, L. and Öhlander, B. (2010) Green liquor dregs for the amendment of tailings. *13th International Seminar on Paste and Thickened Tailings*, Canada.

Midžić, S. and Silajdžić, I. (2005a) Macedonia. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 21-23.

Midžić, S. and Silajdžić, I. (2005b) Serbia and Montenegro. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 18-20.

Miseré, W.M.H. and Wings, R.W.M.G. (2004) The Netherlands – rising mine water in the former Dutch coal mines. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 168-170.

Neuschütz, C. and Greger, M. (2008) *Establishment of vegetation in sewage sludge used in dry cover treatment of mine tailings*. Technical report. No 2008-14. 36p. (in Swedish) Svenskt Vatten AB.

Nurmesniemi, H., Pöykiö, R., Perämäki, P. and Kuokkanen, T. (2005) The use of a sequential leaching procedure for heavy metal fractionation in green liquor dregs from a causticizing process at a pulp mill. *Chemosphere*, **61**, 1475–1484.

Pantó, G. (1956): *A rudabányai vasércvonulat földtani felépítése [Geological structure of the Rudabánya Iron Ore Ridge]*. Yearbook of the Hungarian Geological Institute, 44/2, 329-636. (in Hungarian).

Puura, E. (2004) Estonia. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 166-168.

Räisänen, M.L., Heikkinen, P., Pulkkinen, K., Korkka-Niemi, K. and Salonen, V-P. (2005) Finland – mine water quality in some abandoned and active Finnish metal sulphide mines. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 5-7.

Sárváryné-Szentkatolany, B. (2004) Hungary. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 1. *Mine Water and the Environment*, **23**(4), 175-177.

Sobek, A.A., Schuller, W.A., Freeman, J.R. and Smith, R.M. (1978): *Field and laboratory methods applicable to overburdens and minesoils*. U.S. EPA, Cincinnati, Ohio, 45268. EPA-600/2-78-054, 47-50.

Somerfield, P. J., Gee, J. M. and Warwick, R. M. (1994): Benthic Community Structure in Relation to an Instantaneous Discharge of Waste Water from a Tin Mine. *Mar. Pollut. Bull.*, 28 (6): 363-369.

Stehouwer, R., R. L. Day, et al. (2006) Nutrient and trace element leaching following mine reclamation with biosolids. *Journal of Environmental Quality*, **35**, 1118-1126.

Walder, I.F. and Nilssen, S. (2005) Acid Rock Drainage from Norwegian Mines. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 2-5.

Witkowski, A.J. (2005) Poland. *In* Wolkersdorfer, Ch. and Bowell, R. (Eds) Contemporary Reviews of Mine Water Studies in Europe, Part 2. *Mine Water and the Environment*, **24**(1), 13-16.

Younger, P.L., Coulton, R.H., Froggatt, E.C. (2005) The contribution of science to risk-based decision-making: lessons from the development of full-scale treatment measures for acidic mine waters at Wheal Jane, UK. Science of the Total Environment, 338, 137-154.