Flooding of WISMUT's uranium mines after closure – Key findings and unexpected effects[1]

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ABSTRACT

The closure of five underground uranium mines is a central issue of the WISMUT project. Based on extensive investigations, controlled mine flooding was identified to be the most environmentally friendly, the technically safest, and hence the most appropriate low-cost option for long term water management. Differing boundary conditions in terms of geology, hydrogeology, and the former mining technology required individual flooding strategies and technological arrangements at the various sites. Comprehensive monitoring programs have been implemented. By 2008 more than 90 % of the underground workings were flooded, and a number of general findings regarding flood water rise, water quality and stratification in the flood water column, as well as geo-mechanical stability of the surface have been made. By means of selected examples, those findings, but also unexpected effects are described and discussed regarding long term challenges.

Additional Key Words: water rise, water management, mine water, environmental impacts

INTRODUCTION

Immediately after the end of World War II, the Soviet occupying power started to explore and mine uranium deposits in East Germany. Until German reunification, a total production of 216,000 metric tonnes had made Wismut AG the world's third largest uranium producer. More than 40 years of unrestricted mining left behind a multitude of unsecured radioactively contaminated waste sites in densely populated regions in Saxony and Thuringia.

In the wake of German reunification, the German federal government took the responsibility to clean up the legacies of Soviet-German uranium mining operations. Among the objects to be remediated were some 1,500 kilometres of open underground workings. With a view to cleaning up and rehabilitating for future reuse the adversely affected mining regions, the German federal government took over the former Wismut AG which was restructured as a government-owned corporation and put in charge of rehabilitating the uranium mining liabilities.

Decommissioning and safe closeout of the former uranium mines was one of the most prominent core tasks under this large-scale environmental restoration project. Upon cessation of uranium mining operations in 1991, mine decommissioning was initiated at all sites. The task at hand consisted of closing out adits, shafts, and mining fields of several large uranium mines with a total volume in excess of 80 Mill. m³ in a technically safe, environmentally friendly, and low-cost way (Paul et al. 2006).

By the end of 2008 decommissioning and flooding of the mines were to a large extent complete. Remaining long-term tasks will be mine water treatment and environmental

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monitoring for many years to come. Experience gained in implementing flood conceptions with due regard to site-specific characteristics and boundary conditions is demonstrated and discussed for 4 selected mine sites.

CHARACTERISTICS OF SELECTED EASTERN GERMAN URANIUM MINES

The former Wismut AG operated a large number of uranium ore mines in the South of the former GDR. In the immediate aftermath of World War II, a lot of smaller mines were developed, in some cases starting from historic ore mines. At a later stage, very big mines were developed with the interconnected Ronneburg mine being the largest and the Schlema-Alberoda mine being the deepest operation going down to almost 2,000 m. More details on the sites are contained in the ICARD Proceedings (Paul et al. 2009).

Comments on the Ronneburg, Schlema-Alberoda, Pöhla and Dresden-Gittersee mines illustrate parallels and differences identified in a number of developments and processes. The Table below (Table 1) lists key characteristics of the mines considered.

Table 1. Key Characteristics of selected Uranium Ore Mines of Wismut GmbH

Mine Site	Ronneburg	Schlema-Alberoda	Pöhla	Gittersee
Operating Life	1951-1990	1946-1990	1967-1990	Century-old coal mine, ca. 500 years, until 1989
Type of Deposit	Black shales	Vein deposit, crystalline rock	Vein deposit, crystalline rock	Bituminous coal deposit
Mining Method	Underground mine, Open pit, ca. 44 Mill. m³	Cut and fill, ca. 10 Mill. m³ self-fill	Cut and fill, room and pillar mining, ca. 0.1 Mill. m³ self-fill	Seam mining and caving, ca. 4,000 t Uranium (uranium-bearing coals)
Mining Voids	Ca. 25 - 30 Mill. m³	Ca. 36.5 Mill. m³	Ca. 1.5 Mill. m³	Ca. 2.3 Mill. m³, ongoing caving
Max. Depth	Ca. 1000 m	Ca. 2000 m, Ca. 1800 m unter Wasserüberlauf	Ca. 800 m, Ca. 500 m unter Wasserüberlauf	Ca. 560 m
Mine Geometry	Interconnected mines extending across an area of ca. 75 km². Isolated subsections, 40 day shafts, 22 levels, 3,000 km headings, plus open cast mine, relatively stable	80 day and blind shafts, 62 levels, 4,200 km headings, relatively stable	Main adit, 2 blind shafts, mine shielded from ground surface by undeveloped overlying rock, relatively stable	Elongated mine workings (25 km²), 3 interconnected mining fields, advanced caving
Non-Floodable Voids	Marginal	Ca. 2 Mill. m³	Ca. 0.5 Mill. m³	Marginal
Flooding status 2007	20-25 Mill. m³	Ca. 36.5 Mill. m³	Ca. 1.5 Mill. m³	Ca. 2.3 Mill. m³,
Remedial Action	Shaft plugging, Hydraulic barriers	Shaft plugging	Marginal	Shaft plugging
Flooding	Since 1998, ongoing, controlled	1991-2004, controlled	1992-1995, uncontrolled	1995-2003, controlled
Strategy	Controlled rise to final level, collection of water flowing out at the surface	Uncontrolled rise up to level of mine drainage tunnel, long-term use mine drainage tunnel	Uncontrolled rise up to main gallery level, long-term use of mine drainage tunnel	Controlled rise to final level, diffuse subsurface drainage without WTP
WTP	Conventional, minimum 20 yrs	Conventional, minimum 20 yrs	Passive biological with redundant WTP	None

ENVIRONMENTAL EFFECTS OF MINE CLOSURE

Mine closure entails various environmental effects, such as:

- Modification of mining-induced hydrogeological conditions, typically groundwater recovery, and as the case may be water logging at the surface, discharge of mineralised flood waters;
- Geomechanical response (heaving/sinking, tectonic events, subsidence);
- Gas release during flooding, release of Radon and Radon progeny, as the case may be.

In the following, comments will mainly focus on aspects of the aquatic pathway.

MINE FLOODING
Given the prevailing climatic and geological conditions, mine workings are largely flooded by groundwater rise due to natural groundwater inflow following cessation of mine water pumping. Wismut was faced with the challenge of designing and implementing each flooding process in an environmentally-sensitive and sustainable manner. Mine flooding was therefore planned and implemented with due regard to site-specific boundary conditions and accompanied by comprehensive monitoring programs.

As humid climatic conditions at the mine sites considered exhibit precipitation of 600-1000 mm/a and an average annual temperature of 7-9 °C, conditions are fulfilled for a positive climatic water balance which induces flooding of the mines when mine water pumping ceases and results in groundwater emergence in the long run. As a consequence and with a view to avoiding long-term mine drainage measures, mine flooding was the fundamental strategy to be chosen.

In doing so, Wismut pursued a fundamental strategy of removing any environmentally hazardous substances (fuels, lubricants, batteries, chemicals, etc.) from underground workings prior to the cessation of mine water pumping. Safe decommissioning also involved work to be performed for hydraulic, ventilation, or rock mechanical reasons.

With the exception of the Pöhla site, mine flooding, i.e. restoration of the groundwater level, was allowed to proceed in a controlled manner either by controlled reduction of mine drainage or by pumping. This helped to ensure orderly abandonment on the one hand and to gain hands-on experience with the flooding process on the other.

Rise to a stable water level marks the end of the flooding process; such ultimate level develops in the long term (a) without any technical means or (b) with the help of minor technical means. Case (a) involves diffuse drainage of mine water discharge while case (b) requires a long-term stable structure (mine drainage gallery) and a certain amount of maintenance work in the long run (Figure 1). Pump and treat option is to be considered as a special case of man-made mine drainage.
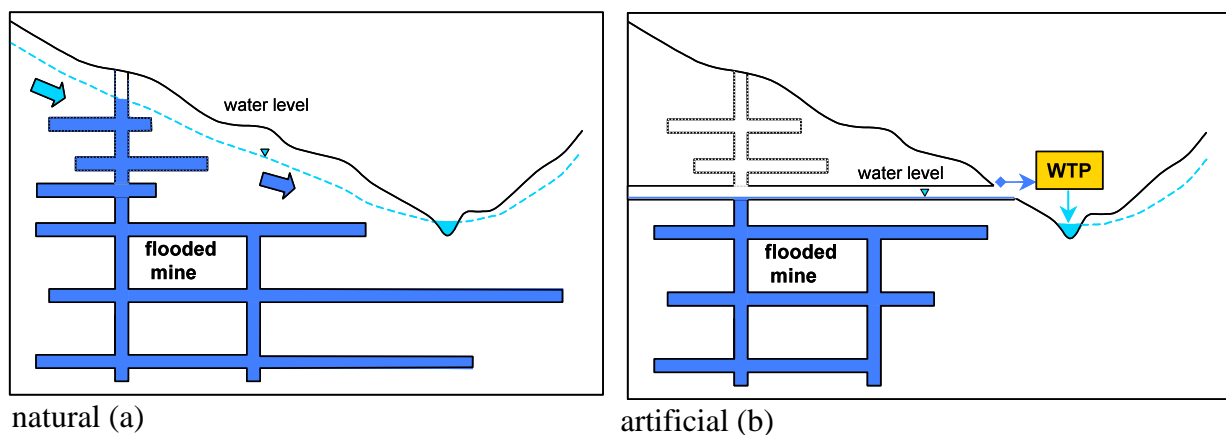

natural (a)   artificial (b)

Figure 1. Water release: natural vs. artificial (WTP = water treatment plant)

In the cases of the Ronneburg and Gittersee mining sites, Wismut acted on the assumption that at the completion of groundwater recovery diffuse subsurface runoff would develop toward the nearby receiving stream. For the Gittersee mine it was estimated that such runoff would completely occur in near-surface aquifers and no mining influenced waters would emerge on the surface.

The area around the Ronneburg mine is characterised by valley cuts (Gessen valley) situated below the predicted ultimate flood water level. A near-surface collection system was established in this area to capture emerging flood water.

Relatively small in size, the Pöhla mine was developed through an adit cut into a hillside with the majority of its underground workings located below the adit level. Therefore, it could be expected that once flooding of the mine was complete long-term water outflow would occur via the main adit.

Conditions are very similar to Pöhla at the significantly larger Schlema-Alberoda mine where a historic mine water drainage tunnel was available for the overflow from the flooded mine.

KEY FINDINGS

Groundwater recovery

The initial mine flooding concept for the Ronneburg[2] mining site was based on the assumption that it would take the flood waters 12 to 15 years to emerge at the mine's deepest overflow level (Gessen valley at ca. 240m a.s.l.) (WISMUT, 1993). At that time, the earliest possible overflow was estimated at 8.5 years, however, this scenario was considered as extremely unrealistic and therefore discarded in further planning stages to establish flood water collection and treatment facilities. The actual time span for groundwater to rise to the above mentioned reference level amounted to almost exactly 9 years (beginning of 1998 – end of 2006). Major reasons for this speedy rise included (i) a slight underestimation of average inflow volumes, more importantly, however, (ii) a partly considerable overestimation of flood-relevant pore volumes in the dewatered rock, in backfill material as well as in the floodable section of the backfilled Lichtenberg open pit mine. Nevertheless, the necessary technical facilities and structures were ready in time and on line when required.

Uncontrolled flooding of the Pöhla mine up to the overflow level (main adit) was predicted to take some 2 years. In fact, it took some 3.5 years to complete. This was caused by a drop in natural groundwater inflow as the flood level rose as well as by geological voids larger than recorded by mine surveying data (karst cavities).

In contrast to Pöhla, flooding of the Schlema-Alberoda mine initiated in 1991 was quicker than predicted. Despite temporary pumping phases, the considerably larger mine workings at this site filled up much quicker than expected since the predicted flood-induced inflow drop failed to materialise. As a consequence construction of the planned water treatment plant was sped up and its treatment capacity augmented.

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[2] Comments on the Ronneburg mine are restricted to the mining fields situated to the South of the German Federal Motorway BAB 4. These fields are by far the most important mining operations of the district and they are hydraulically isolated from the mining fields to the North.

Final flooding of the Gittersee mine was conducted in 3 stages and took some 9 months to complete. This corresponds more or less with the predicted time span of about 1 year.

Water drainage
As originally planned, water discharge from the Ronneburg mine started in August 2006 to use a near-surface collection system based in the Gessen valley and consisting of horizontal, vertical, and surface drains, function wells and collectors. Further flood water rise above the valley bottom, which is still ongoing, made obvious, that an extension of the collection system designed as a basic structure is required, since uncontrolled discharges to the natural creek occurred. Engineering operations are under way to ensure stable and safe mine water collection without adversely impacting the receiving stream running through the valley. The need for the collection system to be extended arose from (i) an insufficient hydraulic range of the basic structure in high yield areas as well as from (ii) water creeping at old boreholes owing to their insufficient state of preservation.

In contrast to Ronneburg, water discharge from the flooded Pöhla mine via the main adit encounters no problems worth mentioning.

At the Schlema-Alberoda mining site, underground workings are flooded right up to the level of a recently engineered drainage gallery. Connected to a pumping well, this drainage gallery runs at a level deep enough to safely preclude any flood water emergence in the Schlema urban area. As long as the water quality needs treatment, the flood water will be pumped to a WTP. In the long-term the flood water may freely discharge via the drainage gallery to the receiving stream, i.e. the Zwickauer Mulde River.

In 2003 the Gittersee mine was allowed to flood up to the natural water level of ca. 180 m a.s.l.. Contrary to all expectations, sufficient diffuse runoff did not materialise, and instead of that water logging occurred in the Freital urban area. Following repeated hydrogeological investigation, the original concept of diffuse runoff had to be discarded as it was unfit to ensure long-term runoff while safely precluding any surface emergence in the urban area. As a result of a renewed analysis of options preference was given to a project to extend by some 3 kilometres the historic Elbstolln drainage gallery. This engineering measure ("WISMUT-Stolln") is currently being implemented. Upon its completion in 2011 it will permit to safely collect any flood water in the ground below inhabited areas.

WTP Capacity Dimensioning
Early in the 1990ies there was growing awareness that most of the flood waters emerging from uranium mines would have to undergo treatment before being permitted to discharge to nearby receiving streams. For this reason, planning and design of appropriate WTP began upon pull-out and initial flooding.

The Ronneburg WTP was designed for a treatment capacity of 450 m^3/h with an option to expand the capacity to 600 m^3/h by converting the sludge line. Actual mine water volumes since the WTP went on line varied between 350 and 420 m^3/h depending on hydrometeorological conditions; of that volume ca. 300-320 m^3/h are collected by the Gessen valley facilities which is in fairly good agreement with earlier estimates (250-300 m^3/h, WISMUT 1993).

Based on data of known mine inflow, water balance analyses, as well as with due regard to hydraulic aspects, the volume of flood water emerging from the Schlema mine was predicted

to be in the order of ca. 450 m³/h. Capacity dimensioning of the WTP was done accordingly which went on line in 1999 for flood control purposes. When mine flooding was in progress the actual volume levelled off at an average rate of 800 m³/h. As a consequence, the capacity was gradually augmented to accommodate a maximum rate of 1,150 m³/h. In addition to this, a near-surface mine void of ca. 500,000 m³ is available as hydraulic buffer storage facility (stormwater).

The predicted long-term flood water discharge from the Pöhla mine had been in the order of ca. 50 m³/h. A conventional WTP was established in 1994 to treat this volume plus additional volumes of contaminated waste rock pile seepage. As the flood water level rose in the mine, groundwater inflow decreased significantly. Currently, the runoff has levelled off at an average rate of 14m³/h. What's more, contaminant concentration levels were also decreasing, as a result the conventional WTP was phased out in 2004 to be replaced by a passive-biological treatment facility which is still in test operation (Küchler et al. 2005)

Drainage from the Dresden-Gittersee mine to the Weißeritz River was predicted to be in the order of 80 - 100 m³/h. This volume was corroborated during pumping measures during the mine's staged flooding as well as during operations to lower the water level to permit construction of the WISMUT-Stolln. Following completion of the construction work as tapping will be from a lower level, the estimated runoff will be in the order of ca. 80 m³/h. Based on geochemical investigation data (see following paragraphs) one starts from the assumption that flood water quality will comply with discharge standards for direct discharge into the Elbe River.

Flood water quality trends
As the result of mining activities, geochemical reactions, mainly oxidation processes, occur in the host rock, and more or less high levels of water soluble contaminants are stored within the mine, mainly sulphate, heavy metals and natural radionuclides. By flooding the mine this contamination potential is taken up by the inflowing groundwater becoming mine water with relatively high mineralisation and contaminant concentrations. Later dilution by groundwater inflow predominates, and contaminant levels in the mine water begin to drop. Oxidation reactions will be reduced by saturation of the rock and exclusion of atmospheric oxygen. Experience from flooding operations at different mines has shown that the duration of the time span with elevated concentrations, the so called first flush, equals about four times the flooding period (Younger et al. 2002).

Homogeneity / Inhomogeneity of the mine waters
The Ronneburg mine is a complex system of interconnected, formerly individual mines, which during operation were characterized by very different water qualities, since a substantial portion of the mine water contamination has its origin in contaminated seepage of huge waste rock piles, which were scattered over the entire site. Accordingly, a very inhomogeneous flood water body has developed during the flood water rise. Since 2006, when mine waters started to discharge into the water collection system described above, the water quality of the different mine fields exhibit a certain tendency of equalization due to mixing processes along the flow path.

The Schlema and Pöhla mines are characterized by widely homogenous mine water bodies as a result of good hydraulic connections within the underground workings and of enforced convection by geothermal processes. Given that there are similar water qualities everywhere, there is no problem with the flood water tapping level from a contaminant perspective.

The mine water body at the Gittersee mine shows a significant stratification with higher mineralised water at the deeper levels. From a contaminant level perspective the point of overflow should be as high as possible as it would permit to tap the overlying clear water stratum which in turn is fed by low mineralised infiltration waters so that water treatment measures might be redundant.

Hydrogeochemical Processes

Since flooding of the Pöhla mine was complete, the flood water volume was renewed about 1.5 times (restocking the water volume takes some 8 years). However, the rapidly diminishing uranium and sulphate levels at Pöhla cannot be explained by dilution alone. In addition to solution and dilution, chemical reduction processes, catalysed by micro organisms, occur and are able to change water quality. The Pöhla case is a good example of such processes, which can function as natural attenuation. After only about three years, sulphate and uranium levels in the discharging mine water were found to have significantly decreased below the discharge limits. This is caused by favourable conditions like a deep, isolated and relatively small flood water body, low influx of oxygen rich ground water and microbiological activity, which leads to strong reductive conditions and demobilisation of redox-sensitive compounds. In contrast to this the recent development of Ra and As concentrations shows no decreasing trend. Radium is bound among others things in sulphate minerals such as gypsum and barite. At low sulphate concentrations (less than 5 mg/L) dissolution of such mineral occurs and Radium is being released. In terms of radium, there is no way to make a defensible estimate of the contaminant inventory.

Rocks in the Western Ore Mountains commonly contain arsenic minerals, native arsenic and arsenides in particular. At the Schlema and Pöhla mining sites there was large-scale opening up of such minerals. Exploratory analysis of original samples has shown that arsenic may be released at g/L levels by aqueous extraction. It appeared in particular that native arsenic contains elevated levels of As_2O_3, exhibiting a relatively high solubility of ca. 18 g/L. Here too, it was impossible to draw up a defensible estimate of the inventory available throughout the mine workings.

As a consequence of the findings discussed above, continued mid- to long-term water treatment appears to be necessary for radium and arsenic (Figure 2).
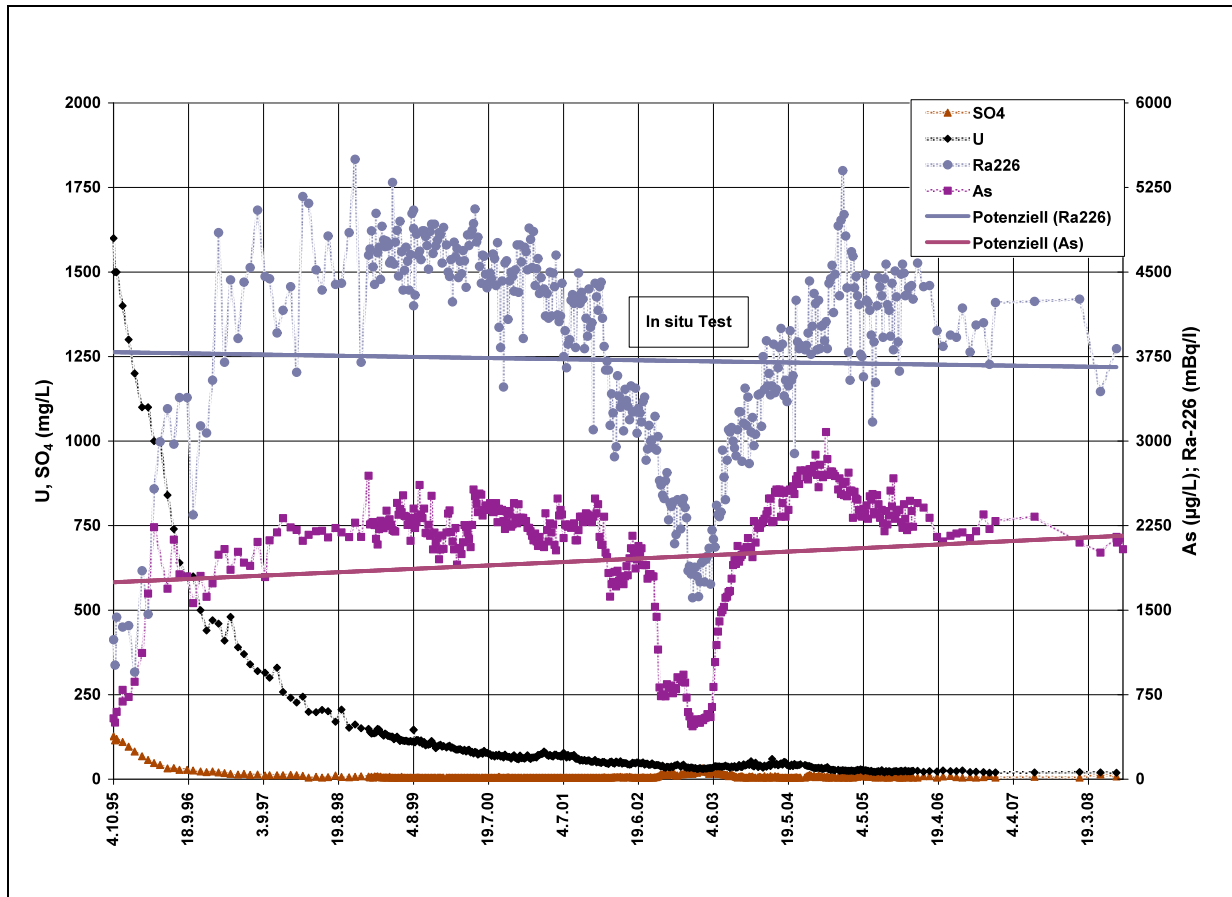
Figure 2. Concentration versus time plots of relevant parameters in flooding water of the Pöhla mine. The time span of an in-situ Test executed in 2002/03, leading to a temporary drop in radium and arsenic concentrations, has been indicated (see Paul et al. 2006).

With regard to its geological and hydrogeological aspects, the Schlema mining site bears a strong resemblance to the Pöhla mine. In contrast, its size is almost 30 times that of Pöhla and its large-scale underground workings reach up close to the surface. As a consequence, the void subject to flooding is considerably larger and hence less responsive, and entry of oxygen and oxygen-saturated waters is relatively high.

Estimates are that so far the flood water volume has undergone almost one complete renewal. Concentration series (Figure 3) very clearly illustrate the "first-flush"-effect with the time-shifting stemming in the first place from differing mineralisation levels in different water depths. Starting in about 2000, all relevant contaminant levels are on a decline. Knowledge gained so far tends to explain this phenomenon by dilution with incoming low mineralised groundwaters. Like at the Pöhla site, the arsenic level appears to level off at a relatively elevated concentration. Radium concentration level is below that of the Pöhla site. In this case, the relatively high sulphate concentration appears to have preserved its attenuating effect. As the influence of oxidation in the near-surface area exerts a reverse effect in the presence of good convection it remains to be seen whether reducing conditions well develop and consequently lead to very low uranium and sulphate concentration levels.
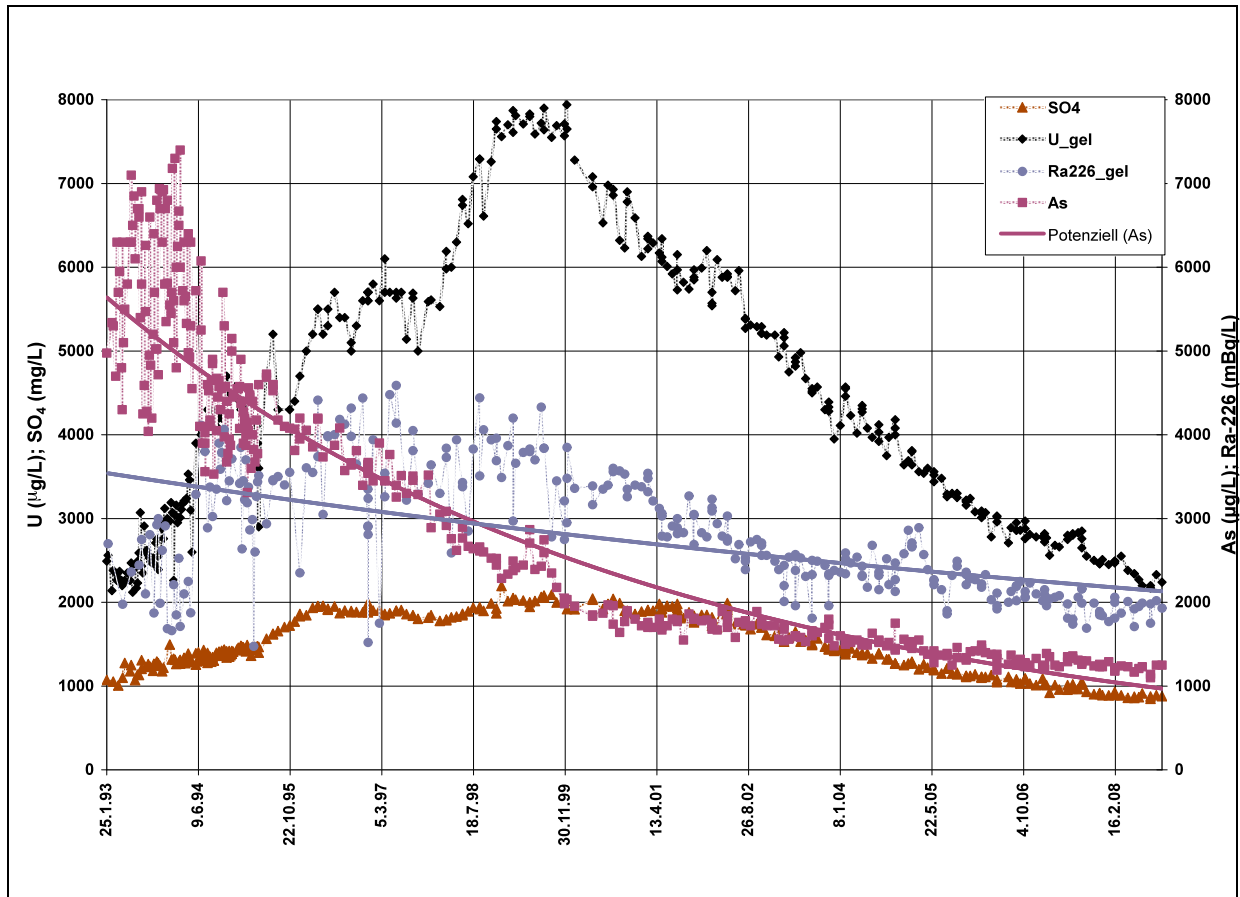
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Figure 3. Concentration versus time plots of relevant parameters in the flooding water of the Schlema mine.

Flood water in the Gittersee mine has a higher mineralisation rate of neutral salts but lower concentrations of heavy metals and natural radionuclides. This situation is caused by the predominating coaly matrix (reducing conditions) as well as by the high sorptive capacity of the sedimentary, clay-bearing host rock (caving, large surfaces).

CONCLUSIONS

Upon cessation of mine drainage, ore mines located in humid climatic zones tend to fill with rising groundwater whereby substances mobilised by mine development will be dissolved. In the absence of control, such waters end up in nearby aquifers or receiving streams and generally have a negative environmental impact upon them. Groundwater rise can be controlled. Such control helps implement measures during pull-out with a view to mitigating environmental impacts. Flood water discharges may either occur as diffuse subsurface runoff with or without any direct effect on the ground surface, or in a conventional manner by mine drainage structures (galleries, pumps). With regard to their environmental effects, mine flooding operations constitute complex systems involving reverse processes.

Predictions made under the Wismut Project of groundwater recovery, flood water emergence and future mine water quality were not always corroborated by reality. Unsurveyed mine voids may have significant impact on groundwater recovery. Such voids are primarily karst cavities, historic mines, and exploratory boreholes in a precarious state of preservation.

The importance of varying inflows during the flooding process should not be underestimated. Flooding-induced tectonic effects may significantly modify the properties of joint aquifers. Comprehensive metrological monitoring allowed in-depth identification and partial quantification of processes.

Favourable conditions may permit sustainable diffuse discharge, practically free of charge. This option presupposes adequate mine water quality at the overflow level (stratification) as well as sufficient hydraulic conductivity. Technical means used for mine drainage purposes require permanent care and maintenance. During the initial years of mine flooding there is a high probability of contaminated waters which will have to be treated in compliance with pertinent regulations. Homogenisation of the flood water body was observed after rising to the overflow level. This is consistent with conclusions in (Younger et al. 2002)

The time span of elevated contaminant concentrations depends on a number of key boundary conditions such as mine geometry, in-mine hydraulics, contaminant inflow, available contaminant inventory, self-purification effects, etc. To some extent these boundary conditions can be manipulated by using technical means. Observations of the mine flooding under the Wismut Project permitted to identify such boundary conditions and to evaluate their overall effects. There is potential for post-closure measures to be brought in line with these boundary conditions with a view to save cost (Paul et al., 2006).

Mine development proposals should consider the experience gained with a view of optimising after-care design planning. Closure strategies should be sufficiently robust and flexible to accommodate major environmental effects in addition to mine-related aspects.

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