Passive Biological Treatment Systems of Mine Waters at WISMUT Sites

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Abstract. Water treatment is an important component of WISMUT's remediation activities at uranium mining and milling sites in Eastern Germany, from both an environmental and financial perspective. In most cases, uranium, radium and arsenic are the main contaminants, while at some sites, nickel and other non-radioactive metals are present too. Passive systems are an attractive alternative to conventional treatment facilities. Numerous approaches have been developed that use natural processes to remove metallic contaminants from mine and seepage water. However, implementing biological water treatment systems is still often regarded as "tricky", and scepticism as to their effectiveness and stability is prevalent among practitioners, the public and, perhaps most importantly, regulators. This paper addresses the regulatory and compliance issues, some of the key issues in the development and construction of such systems, and discusses practical examples of passive mine water treatment systems that have been completed and evaluated by WISUTEC already.

Instruction

Passive water treatment technologies, such as wetlands, are an attractive and economically sensible alternative to conventional technologies at abandoned mine sites for long term water treatment and relatively small contaminant loads. Water treatment is an important component of WISMUT's remediation activities at uranium mining and milling sites in Eastern Germany. Apart from water from tailings ponds, which are treated in conventional facilities, seepage waters from waste rock piles, tailings dams, and smaller mines also require treatment before they can be released into streams but do not warrant conventional treatment due to their low flow rate and the long-term nature of the contamination. In most cases, uranium, radium, and arsenic are the main contaminants, while at some sites, nickel and other non-radioactive metals are present too. For these waters, passive systems are an attractive alternative to conventional treatment facilities. Numerous approaches have been developed and discussed in the literature that use natural processes to remove metallic contaminants from mine and seepage water. Plants and microbes create hydrochemical conditions that lead to a shift of pH or redox potential; in other cases, adsorption or the incorporation of metals in the microbial and/or plant metabolism can be used to reduce the contaminant concentration in the outflow.

WISUTEC, a fully-owned subsidiary of WISMUT, has successfully designed and implemented a number of constructed wetlands for the treatment of waters from WISMUT's mining, industrial, and ore milling sites. Theoretical explanations are available for the chemical and physical processes in constructed wetlands, and the basics seem to be well-understood, in principle. However, implementing biological water treatment systems is still regarded as "tricky" by practitioners, the public and, perhaps most important, regulators. Long-term stability and resilience with respect to external perturbations are a major concern for both wetland operators and regulators. In addition to concerns about potential failure scenarios that lead to a full or partial breakdown of a wetland's function for a certain time, the time a water treatment system needs to restore its function after a breakdown and whether it will fully return to its designed state of operation at all must be considered before approval will be given by regulators.

A necessary precondition for the approval of wetlands by regulators, particularly if radioactive components in the water attract enhanced attention from the public, is that safe operation can be guaranteed over a long time span. Here we are faced with a dilemma: on one side, passive treatment systems derive their attractiveness from the low level of maintenance required, which leads to low costs; on the other side, a certain degree of reliability must be proven before they can be left unattended. This dilemma, combined with the fact that passive treatment systems are not "plug-and-play" technology but need careful adjustment to site conditions and sometimes show seemingly inexplicable fluctuations of performance, is still a barrier to the widespread use of passive systems (Suthersan 2002).

Constructed wetlands as attractive solutions to long-term water treatment at abandoned mining and milling sites

Biological water treatment systems are attractive alternatives for water treatment tasks at abandoned mining and milling sites because of their low operating and maintenance requirements. This general statement will be justified using the experience of WISMUT, the world's largest remediation project for mining and milling liabilities. WISMUT, wholly owned by the German government, is the legal successor to SDAG Wismut, a former Soviet-German company in Eastern Germany, which produced a total of 230,000 tonnes of uranium ore from 1946 through 1991. WISMUT's mining and milling sites are located in the German Free States of Saxony and Thuringia. The federal government committed a total of 6.6 billion € to the remediation of the environmental liabilities. One of the largest single tasks within the WISMUT project is the treatment of effluents from flooded mines and seepages from tailings and waste rock piles. Water treatment consumes about 15% of the total budget and extends over many decades, while other tasks will be finished much earlier. The typical contaminants at WISMUT sites include uranium, radium, iron, manganese, arsenic, and other heavy metals.

The long term trend of water quality at the WISMUT sites is toward decreasing contamination loads. Because neither the required staff nor the dosage of the chemicals in the plant can be decreased below a certain threshold level, the expected decrease of the contaminant loads in the mine water means that while the plant throughput remains largely constant, the specific costs for removal of a unit of contaminant will continuously increase. Contaminant concentrations decrease relatively quickly several years after complete mine flooding, but then remain at a much lower level for a relatively long time (on the order of decades) which, however, continues to require treatment.

In the schematic diagram (Fig. 1) below, the time-dependent development of the contaminant load and selection of the appropriate treatment technology is shown to relate to the regulatory standards.

The diagram demonstrates that there is a considerable time span over which compliance with regulatory requirements would lead to economically inefficient water treatment if conventional treatment plants were to remain in operation. The conclusion that must be drawn is that over the long term, a technology switch from conventional to alternative treatment methods must be designed.

The development and selection of passive water treatment approaches must fol-

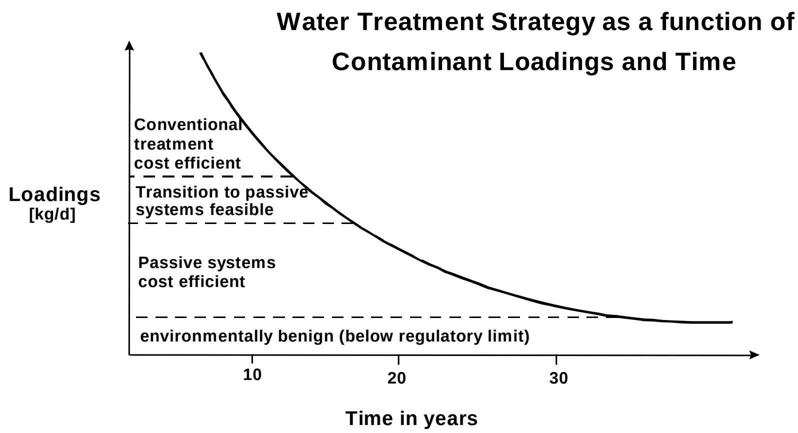

Fig. 1. Typical evolution of contaminant loading and selection of cost efficient water treatment strategy.

low a number of criteria, apart from that of minimizing total costs:

a) The plant must be laid out to accommodate large fluctuations of throughput and feed water quality. The assessment of the amount of water infiltrating into a mine is subject to major uncertainties at the beginning of and during the flooding process. The same applies to the predictions of quality of mine water and waste pile seepage.
b) Residue generation must be small: Residue minimisation follows from the need for cost and risk minimisation. On-site residue disposal must be ensured for the entire duration of the anticipated operation of the plant and even beyond.
c) Self-regulating systems should be considered. Preference should be given to technologies that operate reliably with minimum input and control, and with a high degree of robustness and resilience. This requirement is based on more than cost; over an anticipated operation time of some decades, loss of institutional control cannot be entirely precluded.

Taking advantage of the international experience, WISMUT/WISUTEC, in co-operation with external partners, have been testing various approaches and design principles for constructing wetlands at many sites. Several passive water treatment systems are presently in the stage of technology development and pilot scale field testing. In October 2004 the first constructed wetland for continuous operation took up the test run.

Constructed wetlands at WISMUT sites: The Poehla case

In this section, we focus on the results obtained from a constructed wetland at the Poehla mine site. The Poehla site comprises a relatively small mine with a flooding volume of 1 million m³. In 1995, contaminated flood water reached the level of natural overflow to the surface, at a flow rate of about 15 m³/h. A conventional chemical/physical water treatment plant was commissioned in 1995 to remove U, Ra, As, Fe, and Mn from the mine effluent. Table 1 shows the development of relevant contaminant concentrations in the water from 1995 through 2001.

It is obvious that only manganese, iron, arsenic, and radium require treatment, while the other components have already reached concentrations below the dis-

Table 1. Contaminant loading of the Poehla-Tellerhäuser mine water (main components, average values in the 2nd half of 1995 and in 2001) and the permitted discharge concentrations of the water treatment plant.

Component	Unit	Concentration		Discharge limit
		2nd half of 1995	2001	
U_{nat}	mg/l	1.6	0.1	0.2
Ra-226	Bq/l	1.4	4.3	0.3
As	mg/l	0.9	2.2	0.1
Fe	mg/l	17	8.0	2.0
Mn	mg/l	3.7	0.7	2.0

charge limit. However, water treatment must continue for the remaining components in the overflowing mine water, and geochemical modelling predicts that this will continue over approximately 15 years.

In summer 1998, the first constructed wetland of Wismut was put into experimental operation, treating part of the Poehla-Tellerhäuser mine water overflow. Its schematic layout is shown in Fig. 2. Fig. 3 shows the Poehla experimental wetland in 2003. The constructed wetland was placed in a former concrete water retention basin, which was subdivided by concrete walls into five compartments so that various chemical/physical and biological environments could be created at each stage. Upstream was an aeration cascade. The water movement was achieved by an overall gradient across the system, so that no pumping is needed. In the aeration cascade, the ferrous iron dissolved in the flood water was oxidized. In the neutral flood water, iron hydroxide was precipitated to which arsenic and radium are bonded by adsorption. The iron hydroxide flocs sediment in basins 1 and 2 of the constructed wetland. Basin 2 was provided with specific features: planted floating mats, coconut mats und “AQUA-mats®”. Afterwards, the flood water passed two basins which contain gravel and crushed rock of different granulometry with the water being conducted along the bottom from the first to the second basin. The fill material serves as colonisation area for microorganisms and as filter. The surface of the second gravel basin was planted with helophytes in order to promote the development of biofilms. The final stage of the pilot plant was a planted bottom filter. The reaction space is filled with compost and gravel. The flow is horizontal. In the light of upfront tests, local helophytes were chosen for planting the second gravel basin and the bottom filter area: Typha latifolia, Juncus inflexus, Juncus effusus, Phragmites communis and Iris pseudacorus. Downstream of the constructed wetland are a number of filters filled with reactive material to reduce residual concentrations of arsenic and radium (basin 6 and 7).

Fig. 4. shows the concentration of the relevant contaminants along the sampling points indicated in averaged over a period of 12 months. In the years since installation of the wetland it was demonstrated that it can be successfully used for re-

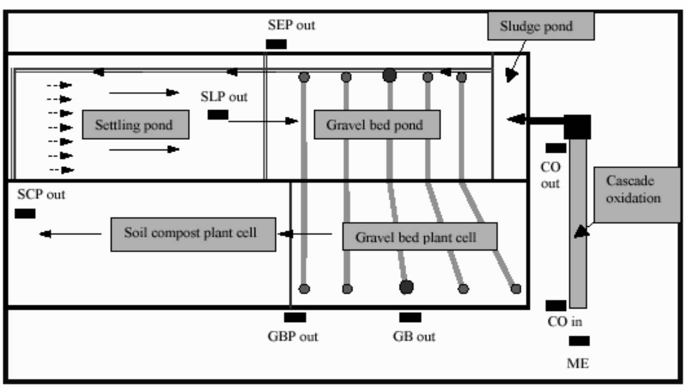

Fig. 2. Schematic layout of the experimental constructed wetland Poehla site.

Fig. 3. Photograph of the pilot-scale wetland at Poehla.

moval of the relevant contaminants at this site. The average removal rates over the last years were: radium, approximately 73%; iron, approximately 97%; manganese, approximately 90%, and arsenic, approximately 83%.

A detailed discussion on the various processes taking place in the system can be found in (Kalin et al. 2002).

The priority task was to intensify both radium and arsenic removal using biological effects. With this objective in mind, investigations were started on the use of macrophyte algae. Accumulation of Ra-226 by various algae species is the subject of intense studies. the continuous black line in the Fig. 5 show in a condensed form the correlation between the specific Ra-226 activity in algae and in feed waters. Investigations conducted by Boojum Research Ltd. demonstrated that some stoneworts species – Characeae – are capable of accumulating considerably higher radium activities. Deviating conditions are indicated in the Fig. 5 by the broken line.

In tests proof was furnished that Characeae are capably of safely removing radium and arsenic from mine water.

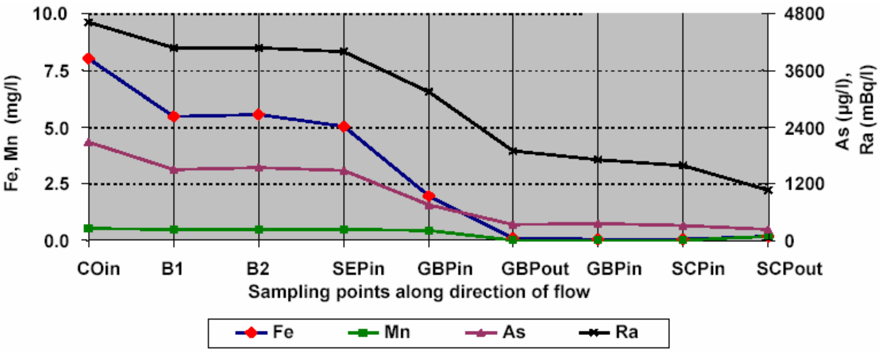

Fig. 4. Contaminant concentration at sampling points along direction of flow through wetland

However as a rule, it will take several growing seasons for purely biological treatment stages involving areas established with algae or plants to reach their full performance. Also, there may be strong seasonal variations, and in a worst case scenario treatment capability may be completely lost.

Under a WISUTEC research project, reactive materials were developed and tested for the selective removal of radium and arsenic from contaminated mine waters. From these investigations, two reactive materials were selected for further testing at the Pöhla site. One of the materials is "Ferrosorp", a granulated ferric hydroxide. This material is particularly suited for arsenic removal. The second material, called "Hedulat", is also granulated and consists of feldspar in a porous matrix. This product is specifically aimed at radium removal. This radium sorbent has been specifically developed by WISMUT/WISUTEC and partners for passive water treatment purposes; more details can be found in (Kunze et al. 2002b).

In 2001, a separate test section was started to remove residual concentrations of arsenic and Ra-226 from the outflow of the pilot plant. In the scheme of the pilot plant, this unit is represented as treatment basins 6 and 7. The channel is subdivided into two sections, section 1 is filled with "Ferrosorp", section 2 is filled with "Hedulat". During the investigation period of one year, the arsenic level was reduced from an initial average of 452 µg/l down to < 30 µg/l. The activity concentration of radium was also reduced from an average of 1.210 mBq/l down to 16 mBq/l.

The next step at the Poehla site was the construction of a full-scale constructed wetland which will operate according to the same design principles as the pilot system so that the conventional treatment plant at the site can be phased out and replaced with the passive/biological treatment facility. In October 2004 the constructed wetland for the treatment of any mine water at the Pöhla site took up the test run. Fig. 6 shows the layout of the facility. Fig. 7 shows the constructed wetland in 2004. The design of the plant is based on a stand-by system to provide treatment in the case of repair or maintenance. In an initial process stage, the mine water flows through an aeration cascade. Its inclination follows that of the Schildbachhalde mine dump.

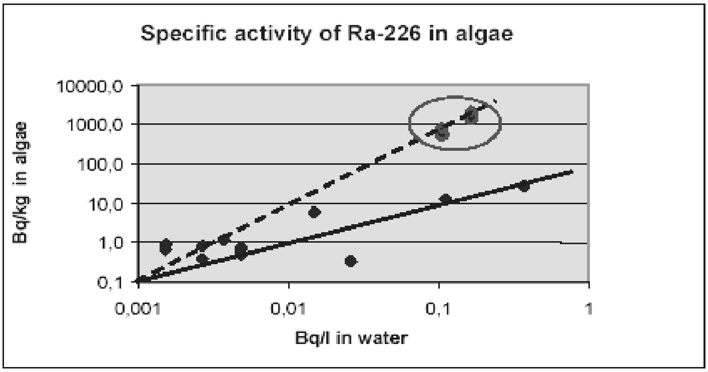

Fig. 5. Specific activity of Ra-226 in algae.

Basins 1 A and 1 B are sedimentation basins in which baffle plate thickener are installed. In these basins, iron hydroxide sludges are separated (Sludge volume per basin: ca. 53 m³). Downstream of the sedimentation basins are basins 2 A and 2 B where AQUA-mats® are installed. In basins 3 A and B as well as in 4 A and B Characeae is established to reduce radium and arsenic concentrations down to compliance with applicable discharge standards. The water level in the basins can be controlled over a wide range and hence be adjusted to the growth of the Characeae. The basins 2A/B to 4 A/B are almost identical in their dimensions (water surface between 483 m² and 535 m², maximum volume between 352 m³ and 386 m³). All basins are constructed as plastic lined earth basins. Tightness of the basins is monitored by drainages running below the basins. Filters F 5 A and F 6 A as well as F 5 B and F 6 B are filled with reactive materials. The water is first flowing through the Hedulat filled filter for radium removal and then through the Ferrosorp filled filter for arsenic removal. The treated mine water is discharged to a receiving stream via an outflow channel.

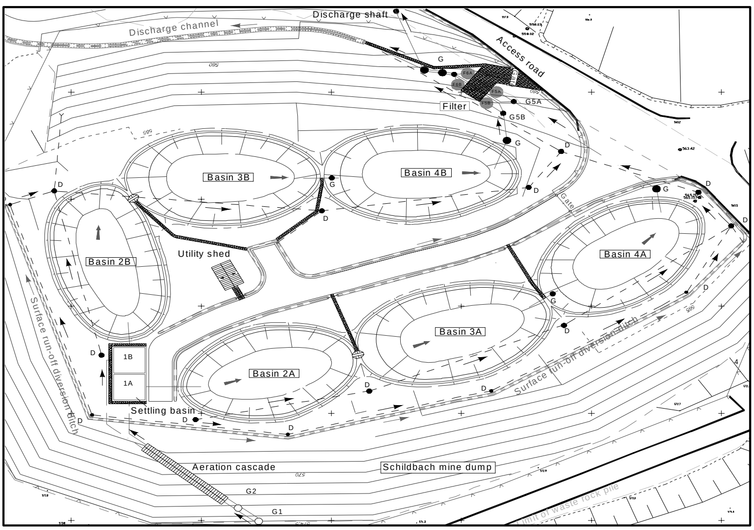

Fig. 6. Schematic layout of the constructed wetland Poehla site.

Fig. 7. Photograph of the constructed wetland at Poehla, Autumn 2004.

The Discharge limits are to be taken from the table 1. The measured average contents of relevant contaminants in input and discharge of the passive biological water treatment facility during the period October 2004 to May 2005 were

- Arsenic: Inflow 2,623 µg/l, Outflow 65 µg/l
- Radium: Inflow 4,430 mBq/l, Outflow 30 mBq/l
- Iron: Inflow 6.6 mg/l, Outflow 0.04 mg/l

In the initial phase where biological processes are not yet involved in contaminant removal, specific costs of mine water treatment are ca. € 1/m^3. As soon as biological processes proven in the bench-scale test will have reached their performance stage, these costs will be down to less than €0.2/m^3.

Robustness of constructed wetlands

As already stated in the introduction, long-term stability and resilience with respect to external perturbations are a major concern for both regulators and wetland operators. There are many approaches to the question of what constitutes a robust system. Definitions and concepts have mainly originated in engineering, biology or sociology, but they are too numerous to be discussed here in detail. With respect to ecosystems, the interested reader is referred to (Jorgensen 2000), which contains a number of interesting concepts. We will confine ourselves to the narrow but practicable terminology of (Gunderson et al. 2000), who uses the terms resistance and resilience as constituents of the broader concept of robustness.

Robustness has to do with the dynamic behaviour of a wetland. Therefore, in order to find a design with high robustness, a dynamic model can be developed based on systems parameters obtained from literature, laboratory tests, or field experiments. Various designs are then simulated under normal operating conditions and external perturbations in order to identify critical design criteria that lead to maximum robustness, i.e. high resilience and resistance, at reasonable cost. This approach has been followed by WISUTEC/WISMUT as part of an R&D project called BioRobust (supported by a grant from the Federal Ministry of Education and Research, operation period 2001 to 2004). A detailed description of the theoretical and experimental work to optimise the robustness of constructed wetlands can be found in (Kunze et al. 2002a).

Apart from laboratory experiments, which produce very valuable parameter sets under controlled conditions, the system’s behaviour under real, site-specific climatic conditions must be considered. An experimental wetland has been built at the waste at WISMUT's Schlema mine site for this purpose (see Fig. 8). The objective will be the Uranium separation in waste waters seeping from waste rock dumps. Emission limit values for arsenic, COD and total nitrogen in the discharge of the plant had been established. The pilot plant consists of two parts which can operate independent from each other. The one pilot plant part is based of systems of macrophytes (area ca. 1,400 m², 4 basins). It consists of 4 basins. Two of the basins were planted with Carex and the others with Phragmites.

The first and second basin operates in surface flow and the following in subsurface flow. The third basin has a management with changing water levels. The other pilot plant part investigate microbiological induced processes for the treatment of contaminated water (reduction area ca. 360 m², 1 basin, 1 aeration cascade in the outflow of the reduction area). The investigated mechanisms include bio-sorption, bioaccumulation, reduction processes.

The discharges from the part facilities will be lead to a lagoon and will then discharged to the local receiving stream. For optimized removing of pollutants molasses and methanol is added to the inflow (seepage water).

The control of the wetland is very complex because of the different condition needed for removal of arsenic (aerobic) and uranium (anaerobic).

It could be shown, that both parts of the pilot plant are able to reduce the contaminant concentration (see Fig. 9). Considerable divergences from normal operation can lead to intolerable operational state.

The lessons learned from the BioRobust project, as they form part of our design

Fig. 8. Experimental multi-cell wetland at WISMUT's Schlema mine site (left: plant cells, right: microbiological cell with gravel bed).

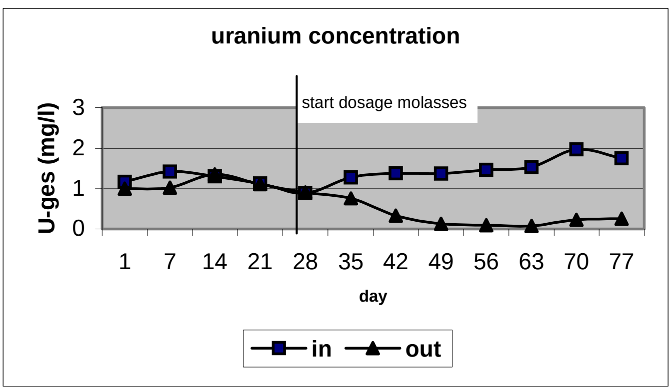

Fig. 9. Uranium concentration in the input and discharge of the planted part of the facility.

principles for constructed wetlands at WISMUT sites and beyond, can be summarized as follows:

- post-treatment filters of adsorption material increase the robustness, especially immediately after inception and/or a temporary breakdown of the biological system
- design-based measures to prevent freezing and to guarantee functionality during winter period
- adjustable overflow level in all ponds/cells
- prevention of surface runoff from flowing into ponds, causing hydraulic problems
- with a minimum of human supervision, small defects can be detected and fixed early, thus preventing larger failure.The pilot plant will be operated after finishing the BioRobust project too. In dependance from the results extension of the constructed wetland area for the treatment of the whole seepage water amount will be planned.

Conclusions and outlook

Since construction of the first experimental wetland at WISMUT's Poehla site in 1998, much has been learned on the behaviour of passive biological systems ("constructed wetlands") for the treatment of mining and mining-related effluents. More solutions using passive biological systems are planned for the WISMUT remediation effort in the near future. These include treatment of seepage of tailings dams and waste rock piles. We believe that from our work to date, highly interesting results and valuable lessons can be distilled and generalised to other sites and other regions of the world. However, each site has its specifics, which means that no plug & play solution exists, in the strict sense exists. Hydraulic and hydrochemical specifics of the site must be carefully analysed before a long-term solution can be devised. This effort is greatly rewarded by a sustainable, robust, low-cost and environmentally appealing solution.

Involved companies in the project

The following companies were involved in the planning and performance of the listed projects: BioPlanta GmbH, Boojum Research Limited, B.P.S. Engineering GmbH and G.E.O.S. Freiberg Ingenieurgesellschaft GmbH.

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