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. Apart from large quantities of water from tailings ponds that are treated in conventional facilities, seepage waters from waste rock piles, tailings dams, and small mines require treatment before they can be released into streams but do not warrant conventional treatment due to their low flow rate and contaminant load, 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 that use natural processes to remove metallic contaminants from mine and seepage water. Plants and/or microbes create hydrochemical conditions which 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. 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.

INTRODUCTION
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).

Another issue is the disposal of the organic and/or mineralised residues that result from the biological activity of a wetland. These sediments, plant and other organic debris is often heavily loaded with the contaminants removed from the water.

Three years of operating a number of pilot systems, among them one constructed to treat mine water from the flooded Pöhla-Tellerhäuser mine of Wismut in Germany, has produced some very interesting results. New selective sorption materials, which are used as final filters, guarantee a high environmental reliability even if the performance of the biological system fluctuates.

In the remaining sections of this paper, we will proceed as follows: first, we will justify the need for passive biological water treatment systems from the point of view of long-term mine water remediation; then we will look in more detail at some pilot-scale constructed wetlands at WISMUT/WISUTEC sites and their practical results; following that, we will report on parallel theoretical and modelling work investigating the dynamic behaviour of constructed wetlands with the proof of resilience and robustness in mind, and finally, we will draw some conclusions and provide a perspective on future developments.

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 Länder of Saxony and Thuringia. The federal government committed a total of 6.6 billion € (about 7 billion US$) 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 economic evaluation of water treatment activities at WISMUT considers total costs, i.e. the costs for the entire duration of the treatment are taken into account including the initial capital costs and the costs of residue immobilisation and disposal. Typical investment costs for the implemented and /or planned water treatment plants under the conditions of the Wismut are in the range from € 7 to 15 million. Operating costs incurred at the treatment plants vary from € 0.75 to € 4.20 per m^3 in Seelingstädt and Helmsdorf, respectively. Operating costs of water treatment, including conditioning and disposal of residues, are dominated by labour costs at relatively low flow rates (for throughputs in the order of some m^3/hour) and by chemical costs at high flow rates (for throughputs in excess of 200 m^3/h).

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 (Figure 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 follow 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.

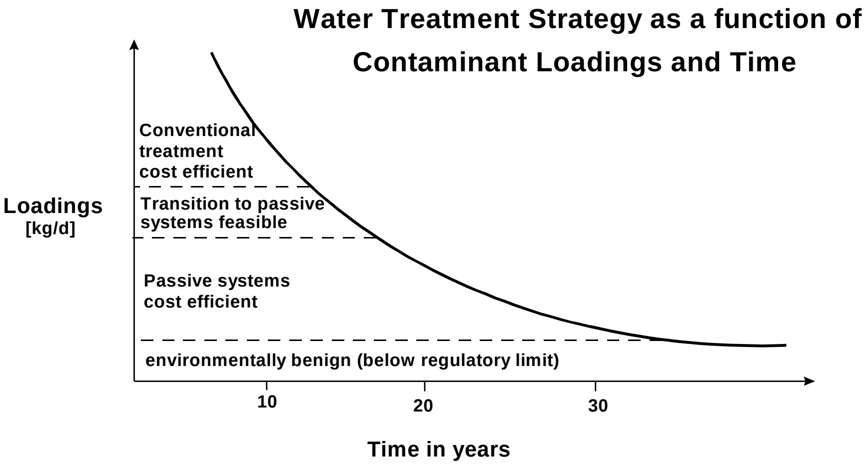

Figure 1. Typical evolution of contaminant loading and selection of cost efficient water treatment strategy

CONSTRUCTED WETLANDS AT WISMUT SITES: THE POEHLA CASE

Passive water treatment systems are presently in the stage of technology development and pilot scale field testing. The required developmental effort in this area was well represented by the large number of contributions at the WISMUT 1997 Workshop on "Water Treatment and Residues Management - Conventional and Innovative Solutions". 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. 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 m^3. In 1995, contaminated flood water reached the level of natural overflow to the surface, at a flow rate of about 17 m^3/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.

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
SO_4	mg/l	140	5	200

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

It is obvious that only manganese, iron, arsenic, and radium require treatment, while the other components have already reached concentrations below the discharge 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 20 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 Figure 2. Figure 3 shows the Poehla experimental wetland in 2002. 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. The water movement is achieved by an overall gradient across the system, so that no pumping is needed. Since early 2000, an aeration cascade has operated at the front end of the system. The throughput through the constructed wetland varies from 1 to 3.5 m^3/h. The system has a volume of 415m^3 covering a surface area of 474 m^2. Two additional small cells are used to test reactive materials after the passive treatment, and are not discussed here. After it has passed over the 21 m long aeration cascade, the mine effluent arrives through a pipe at the bottom of the first cell, a sludge collection cell (2.5x5.8x2.1 m^3). In the first compartment, the oxidation of Fe(II) and the subsequent precipitation of iron hydroxide takes place, followed by sedimentation of the precipitate in the second compartment (settling cell #2). The iron precipitation is accompanied by adsorption of arsenic and radium. From the sludge cell, the water travels along a trough to a larger settling cell (21.4x5.8x2.1 m^3). The water overflows into a gravel bed installed in cell #3 (16.7x5.8.2.18 m^3) where it leaves through 5 drainpipes at the bottom and flows upward into a second gravel bed into cell 4 (17.3x5.8x2.8 m^3). This third cell consists of 0.8 m of gravel, a thin layer of sewage sludge and straw to supply nutrients for plant and microbial growth, covered by an additional layer of 0.4 m of gravel. This 3rd cell serves as a source of nutrients to the fourth cell, where a 1.9 m deep gravel and sand bed is planted with reeds, rushes and cattails, representing the first "wetland" component of the pilot system. The water overflows into the final treatment cell, #5 (23.6x5.8x2.8 m^3) where swamp iris, rushes, reeds and cattails grow in a substrate consisting from top to bottom of a 0.4 m layer of gravel, a 1.16 m layer of soil, followed by a 0.25 m layer of compost.

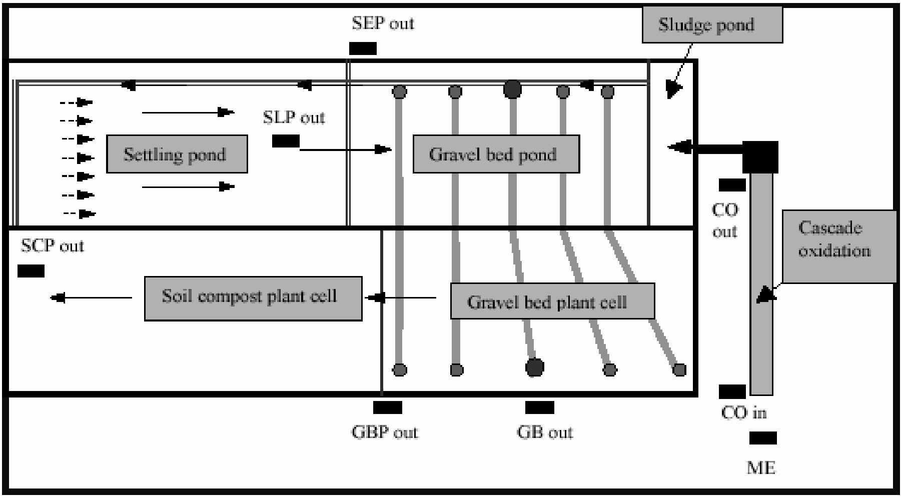

Figure 2. Schematic layout of the experimental constructed wetland at WISMUT/WISUTEC's Poehla site

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

Figure 4 shows the concentration of the relevant contaminants along the sampling points indicated in Figure 2, 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 removal 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%.

After three years of operation, the pilot system has produced some very interesting results. The data show that the system does remove iron, arsenic, manganese and radium and that the removal processes are based on geochemical characteristics of the contaminants. A detailed discussion on the various processes taking place in the system can be found in Kalin et al. (2002). For Mn and Ra, some biologically facilitated removal is suggested through biofilm formation. The monitoring data generated from the Pohla pilot system greatly facilitate the understanding of the natural removal processes at work and have laid a foundation for scale-up following the principles of ecological engineering.

It should be noted that we use special macrophytic algae to adsorb the radium. These algae show a specific sorption capacity that is considerably higher than that of algae and helophytes normally used in constructed wetlands. Figure 5 demonstrates the sorption behaviour on a double logarithmic scale. As these algae are protected by the Nature Conservation Act and cannot therefore be removed from sites where they thrive naturally, we grow them in a special basin.

The Poehla pilot-scale wetland shows a very stable performance during all seasons. This is somewhat surprising but can be explained by mutually compensating processes: though biological activity may be lower in the relatively cold winter, solubility of oxygen in the water is higher, which leads to better precipitation of iron and manganese and thus, at least partially, to better sorption of radium and arsenic. Nevertheless, in order to have a buffer against unforeseen performance fluctuations, a sorption filter for radium is placed at the end of the wetland. Normally, this filter is not needed to retain radium but it can serve as a back-up for many weeks if the wetland fails. 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 brief, it is made of a foamed inorganic alumo-silicate matrix (geopolymer) "doped" with barium sulphate (heavy spar), which is subsequently crushed into a granulate, see Figure 6. It has a very high sorption capacity for radium (well beyond 100 Bq/g, due to triple porosity structure) and an excellent structural long-term stability.

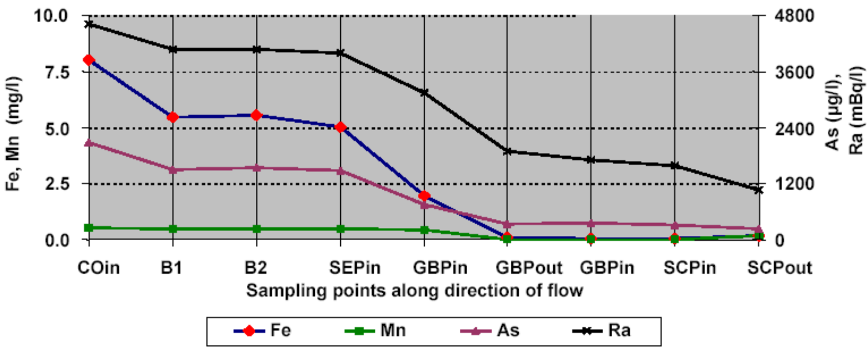

Figure 4. Contaminant concentration at sampling points along direction of flow through wetland

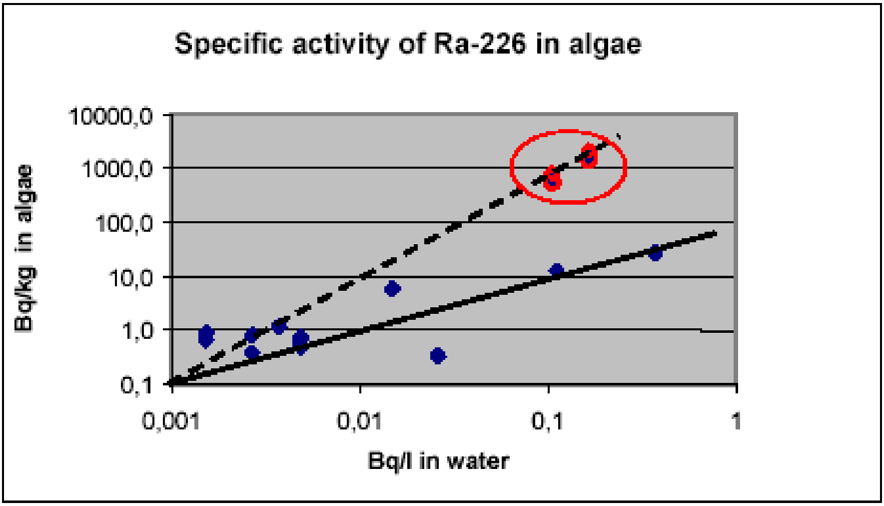

Figure 5. Sorption capacity for Radium of the macrophytic algae used in the Poehla wetland, as compared to average sorption capacity of helophytes

Figure 6. Granulated heavy spar bonded in foamed alumo-silicate (geopolymer)

The next step at the Poehla site is 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. Apart from functionality, the full-scale system is required to fit aesthetically in the surrounding landscape, which has already been recultivated. Planning of the scaled-up system has been completed, and construction will be completed by the end of 2003. Figure 7 shows the layout of the new wetland, consisting of an aeration cascade and 4 ponds performing the same task as the compartments in the concrete basin. It is anticipated that one to two years will be needed to reach a stable performance of the wetland.

A question often raised by concerned citizens and regulators is how to dispose of the residues accumulating in the wetland, particularly the organic material contaminated with radionuclides and arsenic. Although no final concept has been approved, the principal way is clear. The residues to be handled are:

1. Ferrous hydroxide sludge in the sedimentation pond: The amount of hydroxide sludge can be easily calculated from the iron content in the mine water (see Table 1). Approximately 2 tons must be removed from the settling pond and disposed of in a landfill cell on top of a waste rock pile, where the residues of the water treatment plant of the Schlema mine are stored. The sludges will be solidified by Portland cement at the Schlema plant.
2. Material resulting from sorption of contaminants at plants and microbes: Contrary to the notion of contaminated organic material that must be disposed of, the design of the Poehla wetland relies on almost complete mineralisation of algal material. Radium is built into the calcium-rich algal tissue, which then forms inorganic sediments in the wetland. Calculations show that over a time frame of at least a decade, the bottom layer of the wetland will not need to be removed, which greatly reduces the maintenance cost.
3. Spent material from the reactive radium safety filter: If the wetland operates as designed, the safety filter will be replaced approximately every 6 months, and the granulate will be disposed of in the same way as the ferrous hydroxide sludge.

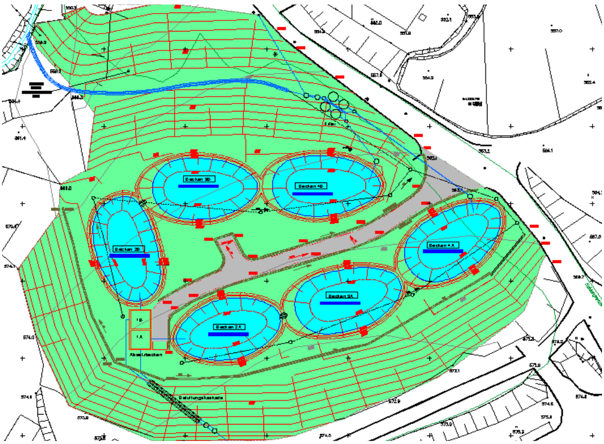

Figure 7. Layout design of the full-scale wetland at Poehla

It is expected that the Poehla wetland will cost around 500,000 € for construction, and require about 2 € per m³ in the first 12-24 months (when a higher degree of monitoring and potential adjustments is expected) for operation/maintenance, which will decrease to about 1.50 € over the long run. This is low compared to more than 4 € per m³ now incurred by the conventional treatment plant. At the average flow rate of 17 m³/h, the anticipated payback time is less than a year.

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 (2000), who uses the terms resistance and resilience as constituents of the broader concept of robustness. Using a physical analogue (potential well model), resilience and resistance can be represented as shown in Figure 6.

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). A detailed description of the theoretical and experimental work completed so far to optimize the robustness of constructed wetlands can be found in Kunze et al. (2002a).

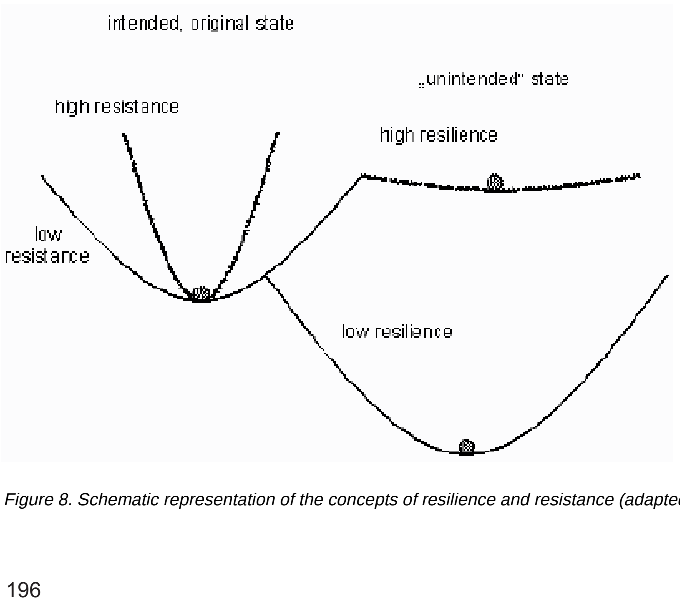

Figure 8. Schematic representation of the concepts of resilience and resistance (adapted from Gunderson 2000)

In order to describe the dynamics of a biological system, we have developed a simple model framework which consists of 3 interlaced parts or submodels: (1) a model for the physical quantities, such as temperature, flow rate etc.; (2) a model describing the removal of contaminants by biological activity, such as microbial growth and microbiologically induced redox reactions, and physical/chemical conditions such as precipitation, sorption etc.; and (3) a model for the biological processes, including a very simple concept of hydrochemical processes, metabolism and nutrient cycle. The concept is graphically represented in Figure 9.

It should be noted that the model is not intended to map the complexity of the real world. Rather, it should provide an understanding of the most important processes taking place in a passive biological water treatment system. With respect to the biological processes, we have restricted the model to the most basic relationships. Submodel 1 primarily aims at replicating the environmental conditions and allows for the simulation of different external scenarios. Monitoring data of the site have been statistically analysed in order to generate realistic time series for temperature and flow rate, including extreme events and correlations between some of the parameters. Submodel 2 links microbial activity and macro parameters such as redox and pH to the removal rates for the contaminants. Submodel 3 is the central component of the model. It describes the dynamics of the microbiological system as a whole (plant and microbial growth, matter and energy cycles).

Two external parameters exhibit the largest fluctuations and are the most critical to determine the dynamic behaviour of the system: flow rate and temperature. The flow rate is characterised by spikes after heavy rainfalls and long periods of draught. In both extreme states, the wetland performance deviates strongly from its design operational state. Temperature also fluctuates, though not as radically, between hot summers and harsh winters in the mountains.

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 WISMUT's Schlema mine site for this purpose (see Figure 10). This multi-cell system consists of two separate parts, each containing a number of individual cells: one is planted with various helophytes, while the other contains installations supporting microbial growth under aerobic and anaerobic conditions. All the cells can be interconnected as required to simulate a specific design.

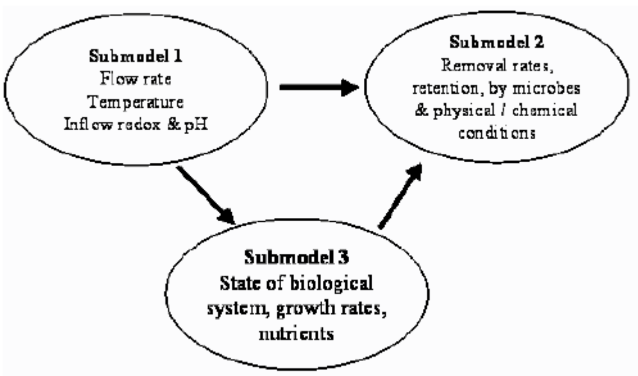

Figure 9. Schematic representation of the dynamic simulation model

Figure 10. Experimental multi-cell wetland at WISMUT's Schlema mine site (left: plant cells, right: microbiological cell with gravel bed)

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

In particular, the use of these principles in designing the Poehla wetland, greatly assisted us in obtaining the necessary regulatory permits.

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. There are already inquiries from international clients to WISUTEC on whether the know-how accumulated at the WISMUT sites can be used elsewhere. 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.

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