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Long-term Stability and Resilience of Passive Mine Water Treatment Facilities: A Joint Experimental and Simulation Approach

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Abstract. Passive water treatment technologies such as wetlands at abandoned mining sites are an attractive and economically sensible alternative to conventional technologies for long time-scales and relatively small contaminant loads. However, long-term stability and resilience with respect to external perturbations are a major concern for both wetland operators and regulators. In this paper, we outline a research project which addresses questions such as resilience and recovery behaviour of passive biological water treatment systems.

Introduction

Passive water treatment technologies such as wetlands at abandoned mining sites are an attractive and economically sensible alternative to conventional technologies for long time-scales and relatively small contaminant loads. However, long-term stability and resilience with respect to external perturbations are a major concern for both wetland operators and regulators. Apart from the investigation of potential failure scenarios that lead to a full or partial breakdown of a wetland's function for a certain time, it is the time a water treatment system needs to restore its function after a breakdown and the question whether it will return to its designed state of operation at all which must be considered before approval will be given by regulators.

In WISMUT's remediation activities at uranium mining and milling sites in Eastern Germany, water treatment plays an eminent role. Apart from mining water and free water from tailings ponds which are treated in conventional facilities, there are a number of seepage waters from waste rock piles, tailings dams, and smaller mines which require treatment before they can be released into streams but do not warrant conventional treatment due to their low flow rate, and due to the long-term nature of their contamination. In most cases, it is Uranium, Radium, and Arsenic which 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 meanwhile been developed and discussed in the literature which use natural processes to remove metallic contaminants from mine and seepage water. Plants and 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 are possible mechanisms to reduce the contaminant concentration in the outflow. Theoretical explanations for all these chemical and physical processes have been developed, and the basics seem to be well-understood, in principle. However, implementing biological water treatment systems are still regarded as "tricky", and scepticism as to their effectiveness and stability is still prevalent among practitioners, the public and, perhaps most importantly, regulators (Suthersan 2002).

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 biological water treatment systems derive their attractiveness from their 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 biological treatment systems are no "plug-and-play" technology but need careful adjustment to site conditions and sometimes show inexplicable fluctuations of performance, is still a barrier to the widespread use of passive systems.

The agenda on the way to better acceptance of passive biological treatment systems for mine and seepage waters is therefore twofold: (1) the chemical, biological and physical processes, as well as their complex interplay, need to be better understood, and (2) reactions of the system to external perturbations, and its ability to return to the normal operating state (i.e., its resilience), must be investigated and optimised. It is primarily the second question which will be addressed in this paper.

Our paper reports on the R&D project "BioRobust" carried out by a consortium of firms. Its objective is to develop a framework to assess the robustness of constructed wetlands and to identify and compare measures to increase the robustness by suitable design and combination of several stages with distinct functionality. Two different types of wetlands are currently being installed at WISMUT's Schlema mining site: a microbiological system based on biofilms on a gravel-bed (G.E.O.S. GmbH), and a plant root system (BioPlanta GmbH). The design of both systems is based on parameters from laboratory experiments in both firms. The data from lab (and, later on, field) experiments are used to develop a system model (B.P.S. Engineering GmbH) which allows to simulate the dynamic behaviour of wetlands.

As of the time of writing this paper, the project is still in progress. This means that there are no final conclusions but a number of promising approaches to be pursued in the further course of our work. This paper does not attempt to give any final answers but to outline our approach.

Concepts of Robustness, Resistance and Resilience

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 may be 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 Fig. 1.

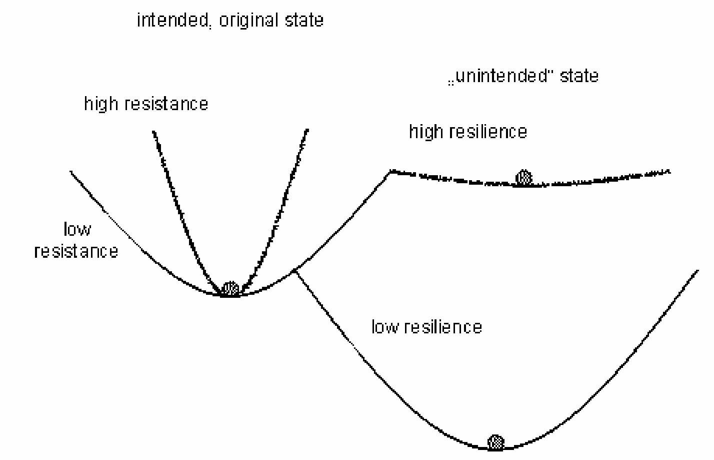

Fig. 1. Schematic representation of the concepts of resilience and resistance (adapted from Gunderson 2000)

It is important to distinguish the concepts of robustness and resilience from that of failure risk. Classical concepts of risk analysis (Renn 1985) ask two questions: (1) how likely is an event, and (2) how severe are its consequences. By contrast, robustness is a term used to characterise the ability of a system to withstand external perturbations and/or to return to the desired operational state after such a perturbation. According to the terminology introduced by Gunderson (2000), robustness comprises the concepts of resistance and resilience. Resistance is a term used to describe the reaction of a system to changes of external conditions, or more precisely the extent to which a system deviates from its normal operating state under the influence of an external force. Resilience, on the other hand, describes the dynamic behaviour of a system after an external shock, and how the system returns to its normal operational state. In the resilience concept, the questions asked are (1) can the system recover after the perturbation is over (or into which new stable state will it move), and (2) how long does it take for the system to recover. Resilience is thus an inherently dynamic concept, and attempts to deal with a system's resilience must start from a dynamic model.

Returning to the issue mentioned in the Introduction that public and regulatory concerns over the long-term behaviour of passive biological water treatment systems are an obstacle to their broader application, we may invoke the resilience concept. Nobody in their right mind would require a passive, unattended water treatment system to function without any fluctuations over many decades. What is required, however, is that the periods during which the system will under perform are short compared to the total operating time, and that the system is able to recover from a wide range of perturbations without human intervention in sufficiently short time.

A practical way of characterising the resistance and resilience of passive biological water treatment systems is thus to provide the following sets of quantities and their interrelationship: the extent of a deviation of performance from the normal state during an external perturbation, the time to recover and the end-point(s) of the recovery process (original state or "lock-in" state other than original). These parameters will often depend on the duration and strength of an external perturbation.

The wetland system can be perturbed by external factors such as

- flow rate fluctuations (dry-out during extended draught periods, or extremely high flow rate due to extreme precipitation events)
- temperature fluctuation (seasonal temperature curve ranges from extremely hot seasons to harsh winters)

These two parameters are likely to have the largest impact on the systems performance. Both flow rate and temperature are subject to seasonal changes and overlaid stochastic fluctuations within a range that can be regarded as normal. In rare events, however, these ranges can be exceeded so that an extreme event occurs. The dynamic system model must be able to describe the behaviour under both situations (i.e., normal and extreme fluctuations), each with its probability distribution or probability of occurrence, respectively.

Other perturbations such as deliberate malevolent destruction may be of theoretical interest but are not part of our investigations because of the breadth of possible scenarios and conceptual difficulty of including them in a coherent framework.

Model Concept

In order to describe the dynamics of a biological system, we have developed a simple model framework which consists of 3 parts or submodels which are interlaced: (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 2.

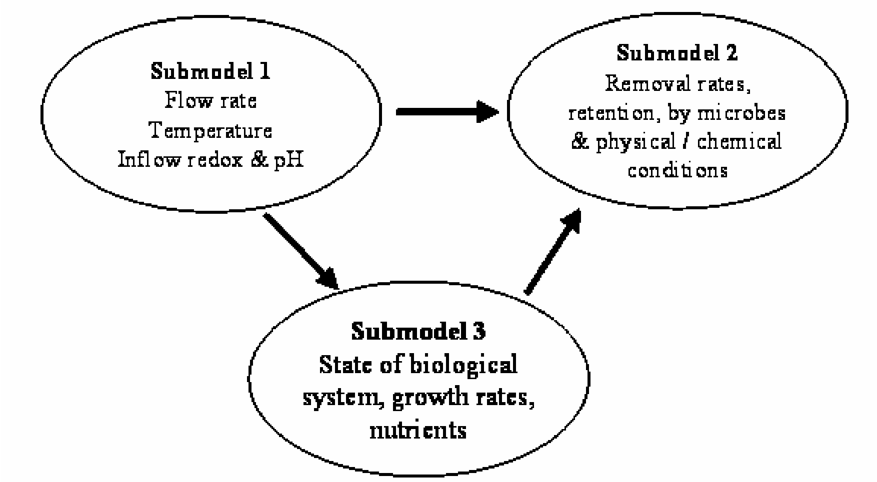

Fig. 2. Schematic representation of the model framework used in the project

It should be noted that the model does not intend to map the whole complexity of the real world. Rather, it aims at giving an understanding of the most important processes taking place in a passive biological water treatment system. With respect to the biological processes, we must restrict ourselves to the most basic relationships.

Submodel 1 primarily aims at replicating the environmental conditions and allows for the simulation of different 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. Alternatively, re-sampling of measured time series and constant values for all relevant parameters can be chosen by the user in order to investigate a wide variety of scenarios and improve the understanding of the complex processes. Some chemical parameters of the inflow water are strongly correlated with the flow rate (e.g., sulphate and nitrate concentrations at the inflow into the passive wetland system). This is due to the fact that different types of water can mix (e.g., different flow paths in a waste rock pile). The model must take this dependency into account. Furthermore, oxygen supply is an important factor which depends on both the oxygen saturation of the inflow water (which in turn is pH dependent) and additional oxygen supply via plant roots.

Submodel 2 links microbial activity and macro parameters such as redox and pH to removal rates. For example, it is now known that Uranium reduction is a process concurrent to sulphate reduction, both processes being mediated by anaerobic microbial activity. Remobilisation is also covered by Submodel 2, for example if anaerobic microbial activity slows down or stops altogether, or redox conditions change due to a breakdown of oxygen consumption in the aerobic zone, so that the solubility of certain contaminant species increases.

Submodel 3 is the central component of the model. It describes the dynamics of the microbiological system as a whole. It is outlined in more detail in the next section.

The dynamic system model is being implemented under iThink, a visual simulation environment similar to the much better known system Stella, both produced by HPS Inc., Hanover NH. It provides the opportunity to create a user-friendly graphical interface which will be a great advantage when communicating the simulation results to the public, regulators or other stakeholders.

Microbiological Submodel

This submodel describes microbial growth and decay. Apart from the biological processes, it must take account of the nutrient balance. Organic carbon, in particular, plays an important role.

We take account of the following processes, in order of their preferred redox range: oxygen consumption by aerobic bacteria, nitrate reduction, sulphate reduction. As an option, complementary processes such as the fermentation of organic matter into alcohol and methanogenesis can be included. Each of these processes is governed by a growth equation of the Michaelis-Menten type, i.e.,

$$dX/dt = X\ \mu_{max}\ c/(k+c) - X/T$$

and a nutrient balance equation or the type

$$dc/dt = -[X\ y + dX/dt\ y']$$

where X is the biomass of a microbial species, μ_{max} is the maximum growth rate, c is the nutrient concentration available to the microbes, k is the Michaelis-Menten constant, and T is the average lifetime of the microbes. y and y' are the consumption coefficients for living biomass and biomass growth, respectively.

Microbial growth of a species occurs until the component reduced by this process is used up. So, if the dissolved oxygen is used up by aerobic oxygen consumption, nitrate reduction sets in until nitrate is completely used up. Only then the sulphate reduction can start, and finally Uranium is reduced to an insoluble sulfidic form.

Each of these processes consumes carbon to build up biomass. It is also partly transformed into carbon dioxide, as is the case in the aerobic zone. Microbial autolysis, on the other hand, sets carbon free which is available for the next cycle.

It must be noted that some of the model parameters (k, T, μ_{max}) are difficult to obtain. Laboratory and literature data can help here, but it is critical that they are valid under site conditions, too. Much work is still needed to establish a reliable dataset. Another problem is the oversimplification of most processes. It would be possible, of course to develop a more detailed multi-stage model of the nitrate reduction, for example. On the other hand it seems questionable that the data required to run such a model would be available. After all, what the model attempts to achieve is a rather general understanding of the basic processes and their dynamics and interconnectedness.

An extension of the model concept described above are macrophytes on the wetland surface. They contribute to the oxygen supply, release carbon compounds via the rhizosphere, and form a basis for microbial growth and adsorption of contaminants.

Summary and Outlook

In a current R&D project ("BioRobust"), the robustness of passive biological water treatment systems for mine and seepage water in terms of resilience and resistance is investigated. Starting from definitions of what we mean by these terms, we have developed a systems simulation model to describe the dynamic behaviour of a passive water treatment system (wetland).

Although we believe that we have reached a good compromise between the complexity of the real world processes and the limits set by a modelling approach, be it the model itself or the available data needed to run the model, much remains to be done both theoretically and experimentally. First of all, two pilot-scale wetlands will be finished at WISMUT's Schlema site. On the theoretical side, macrophytes will have to be included in the model and other refinements made.

We will report on the progress of the project and preliminary results in forthcoming papers.

Acknowledgements

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