Mass Flow Reduction in Mining Water: Valuation of Measures with due regard to the requirements of the Water Framework Directive

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Abstract A case study identified the impact of the Schlüsselstollen, the main drainage tunnel of the abandoned copper slate deposit within the Mansfeld syncline, on the transport of pollutants into the rivers Saale and Elbe with the aim of estimating the impact of potential measures on surface waters and to derive recommendations for action. This was done first for a huge abandoned metal mining area in Germany and the methodology proposed in this case study can be used for valuation of other (abandoned or active) mining sites.

Key words Water Framework Directive, Mine Water, Mine Closure, Mass-flow-reduction

Introduction

Besides other protocols, the Water Framework Directive (WFD 2000) defined the ”aim of achieving good ecological potential and good surface water chemical status by the latest” 2015 which was challenging for water bodies draining huge abandoned mining sites. Following an inventory and assessment of the then current state of the flooded mine workings and the drainage system of the Mansfeld syncline, suggestions for technical solutions should have been made to reduce mass flow of metal pollutants, especially of particle-bound potentially toxic metals in the receiving rivers. The following goals were defined for the case study, which was carried out between 2011 and 2013:

- Balancing of discharge and concentration of pollutants based on long-term measurements
- Data evaluation of particle-bound pollutants from the Schlüsselstollen drain water
- Additional analyses on potentially toxic metals for verification of available chemical analyses
- Comparison between the solute load and total load
- Sedimentation tests with suspended solids in sweet and salty water
- Assessment, valuation and derivation of measures for mass flow reduction with due regard
- to the requirements of the Water Framework Directive

Overview about Mine Works and Mine Flooding

For about 800 years copper slate has been mined within the Mansfeld and Sangerhausen synclines south of the Harz Mountains in the middle of Germany. It was in the 16th century when the first drainage tunnels were driven in the Mansfeld syncline and since 1879 the whole Mansfeld copper slate mining area has been drained by the Schüsselstollen drainage tunnel. This level tunnel is 31.06 km long and one of the longest levels in Europe. It drains into the Saale River via the Schlenze River (see Fig. 1).

After the active mining was closed in 1969 all extraction space was flooded until 1981 and from 1982 until 1992 high saline mine water from the adjacent Sangerhausen mining area was additionally discharged into the mine works via a pipeline and one of the central shafts in the syncline (Bolzeschacht). By the end all the mine water was discharging into the Schlüsselstollen at the so called "overflow point Glückhilfsschacht" (see Fig. 1).

In total within the Mansfeld syncline 44 million m^3 of mined space was flooded and about 150 million m^3 of natural underground space. Mining was carried out up to a depth of about 1,000 m and the mining galleries have a total length of about 1,000 km. The surface of the flooded water body comprises an area of about 150 km^2. Between 1915 and 1968 the average inflow into the mine works was about 30 m^3/min where 84 % was salty water from the level below the Schlüsselstollen and about 16 % was sweet water from the level above (ARGE GFE 1992).

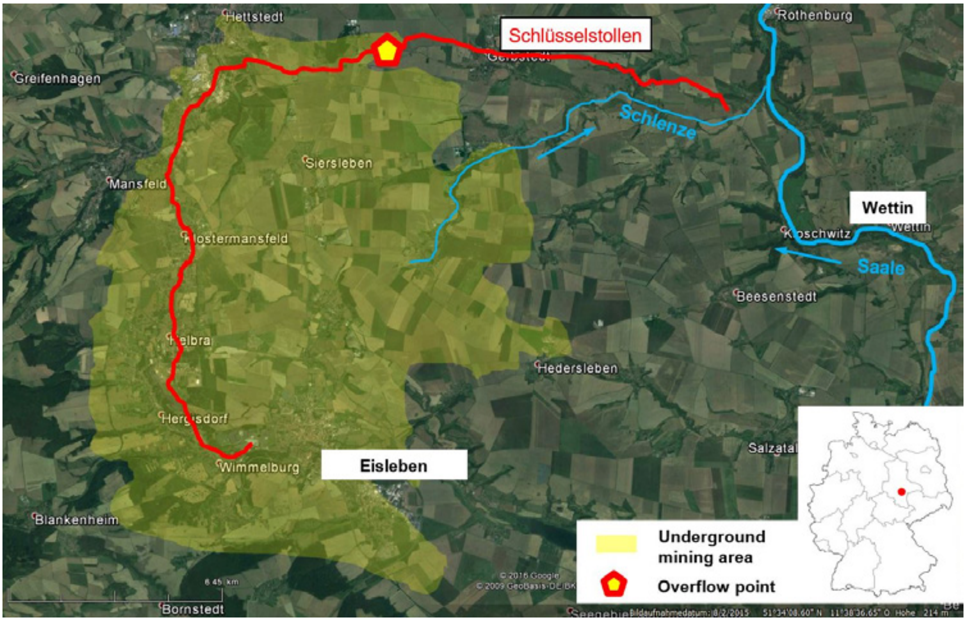

Figure 1 *Course of the drainage tunnel „Schlüsselstollen" and course of the river Schlenze and Saale in der Mansfelder Mulde. Google Earth*

The type and quantity of the ores mined from the copper slate as well as the geological conditions of the deposit determine the type and quantity of pollutants which are discharged together with the mine water into the receiving rivers.

Discharge of the Schlüsselstollen and Mass Flow

Average discharge of the Schlüsselstollen is between 20 and 26 m^3/min but can jump up to 50 m^3/min in the case of heavy rainfalls.

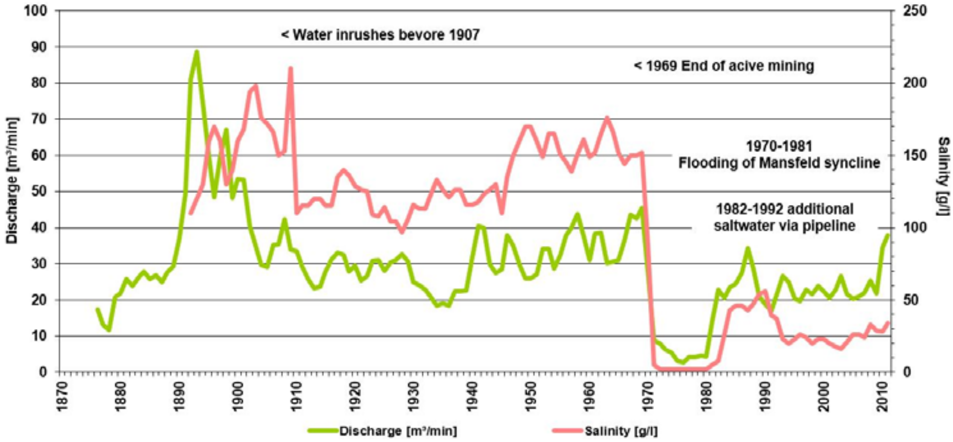

Figure 2 *Discharge and average salinity in mine waterof the Schlüsselstollen, 1876 – 2011*

The flooded mine water table dips slightly from about 81–78 m NN at Eisleben (see Fig. 1) to about 74 m NN at the overflow point. An overview about the development of discharge over the time is shown in Fig. 2.

Annual chemical analysis is available for Na, Ca, chloride and sulphate since 1967 and for some metals (Pb, Cu and Zn) since November 1979. Monthly chemical analysis is available since August 1981 for metals As, Pb, Cd, Cu, and Zn. After termination of the salt water transfer pipeline in 1992 water sampling started for all relevant metals (As, Pb, Cd, Cr, Cu, Ni, Hg and Zn) on quarterly basis. A detailed overview about the distribution of metals in water from different mine adits of the Mansfeld syncline is given in (PLEJADES 2012).

Besides the potentially toxic metals the salt load in the mine water is of major importance for the environment: the annual salt load is about 350,000 t of mainly sodium chloride. Because of the sulfidic origin of the deposit and the high salt concentration potentially toxic metals are transported mainly in dissolved form. Based on a proven methodology (LHW 2012)in years with higher than average discharge (2010, 2011) metal loads of mine water up to 160 t/yr and salt loads up to 600,000 t/yr have been ascertained. Loads for single metals are as follows: 150 t/yr Zn, 3 t/yr Pb, 2.5 t/yr Cu, all other metals (As, Cd, Cr, Ni) about 2 t/yr (PLEJADES 2012). Mercury was also analysed but not detected. Because of an approximate constant concentration of metals and salt in the mine water the mass loads vary accordingly to the discharge of the Schlüsselstollen.

Because of the fact that the discharge of the direct receiving river Schlenze (about 0.1 m^3/s) is less than one third of that of Schlüsselstollen the environmental impact on the Schlenze River is tremendous. The annual average environmental quality standards (EQS-AA) for water and sediment are exceeded for Cd, Pb, Zn, Cu, Ni and As and the maximum allowable concentration (EQS-MAC) is exceeded for Cd. In contrast the impact on Saale River is negligible for some of the metals because of a significantly larger discharge of about 100 m^3/s. Consequently in the Saale River an exceedance of the EQS-AA was only measured at two gauge stations for Zn and Cd.

Description of the Mine System: Flooded Mine Works – Drainage Tunnel

Based on the chemical composition of the groundwater (within the flooded mine works) and of the drainage water along the Schlüsselstollen and at its level mouth, the Mansfeld syncline mine system can be characterised as follows (see Fig. 3):

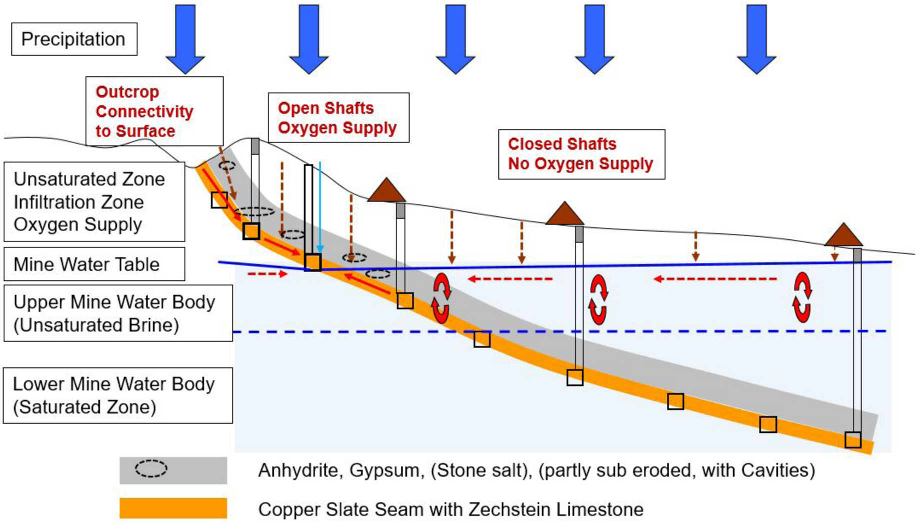

Figure 3 *Flooded Mansfeld syncline – schematic view of the flow conditions in the mine system*

- *Groundwater recharge:* Zone above the flooded mine works (level of Schlüsselstollen), highly saturated with oxygen and with relatively low primary mobilisation of metals. Interaction with the Upper flooded mine water body.

- Upper flooded mine water body above -70 m NN: Zone below the mine water table but above the saturated zone with high concentrations of metals and salt, but not saturated brine. Advective interaction with groundwater recharge and possibility of significant mobilisation of metals.

- Lower flooded mine water body below -70 m NN: Zone flooded with saturated brine, therefore negligible convection and interaction with the upper zone; stable density layering.

The main source of metals is the geogenic sulphide ore deposit. The process of oxidation of water-insoluble sulphides into soluble sulphates is supported by atmospheric oxygen which accelerates the mobilisation of metals. In the high saline mine water the metal sulphates are converted into readily soluble metal chlorides. Atmospheric oxygen supply is caused by groundwater recharge and mine ventilation in a small part of the mine works which is still open for control and maintenance. *The Schlüsselstollen system therefore can be described as a quasi-stable state (with natural fluctuations) with permanent and everlasting mobilisation and emission of geogenic potentially toxic metals*.

Measures of Mass Flow Reduction

According to the Water Framework Directive (WFD 2000) a "good status" had to be achieved by 2015 at the latest. In case the EQSs are exceeded the causes have to be found and measures have to be proposed / realised. In case of point sources (such as mine adits/drainage tunnels) best available techniques (BAT) should be implemented (Article 10, WFD).

Definition of Planes of Action

Generally we can define three planes of action for measures which should be assessed in a first step (PLEJADES 2013):

Plane 1: Measures with direct impact on the source
(Release of pollutants directly from the ore deposit Mansfeld syncline, "up-stream/source")
Measures at the source

Plane 2: Measures with impact within the subsurface migration path
(Mine works and hydrogeological environment within the Mansfeld syncline,
"in-stream")
Measures within the migration path

Plane 3: Measures with impact outside the mine works and adits
(After discharge off the level mouth, down-stream/end-of-pipe")
Measures on the protected (natural) resource

Furthermore an additional – fourth plane of action can be defined which is an administrative measure that describes the existing and achievable status.

Plane 4: Toleration of the status achieved so far and of the future status based on reduced environmental quality standards, if necessary with restrictions for water quality and water usage
(Continuation of recent measures which ensure the operational reliability of the drainage system Schlüsselstollen)
Toleration of the (achieved) status quo

Assessment and Valuation of Measures

Before starting the assessment all measures which were theoretically possible have been described for each plane of action (planes 1-3). Then, in a first step, each measure was assessed individually based on the following main criteria:

- Technical feasibility
- Effort
- Approvability
- Time line for implementation
- Achievement of objectives
- Appropriateness

Daily business shows that, de facto, in most cases ***approvability*** determines feasibility of measures. *Therefore approvability is mandatory for any valuation of appropriate and technically feasible measures*. For a better assessment of the ***appropriateness*** investment cost and maintenance cost (potentially everlasting cost) had to be examined. Furthermore, for better evaluation of the *achievement of objectives* and finally the *approvability* additional ecological / environmental criteria were used which show the possible impact on environmental sustainability:

- Impairment of overall appearance of the landscape
- Impairment of habitat quality
- Danger of remobilisation of pollutants
- Necessity and possibility of disposal
- Improvement of public good
- Evaluation of sustainability

Based on these results, in a second step, a comparative and qualitative evaluation was made for comparison of the measures. Only three measures remained for further assessment:

- Limited feasible measures with a limited impact: chemical immobilisation
- Feasible measures with low or no impact: reduction of (suspended) solids, direct pipeline to the Saale River
- Accompanied measures with low impact: Acquiescence

All other measures had to be excluded from further assessment because of the following reasons:

- Measures which are not executable and measures which are executable but with substantial risk and/or which can only be realised with excessive cost and limited impact:
    - Removal of the source
    - Inclusion of the source
    - Hydraulic immobilisation
    - Reduction of dissolved pollutants
    - In-situ measures of water treatment

- Disproportionate measures (effective technical measures but with excessive cost):
    - Ex-situ measures of water treatment

To ensure an objective evaluation of the appropriateness of measures the ratio between benefit (impact on reduction of pollutants) and effort (cost) was assessed considering the prorated mass flow from the Schlüsselstollen and the total mass flow in the receiving rivers Schlenze and Saale. It also became obvious that all measures which implicate the closure of the drainage tunnel had to be excluded from further assessment:

- Closure of the Schlüsselstollen would cause the outlet of polluted mine water into other water bodies (via other drainage adits on higher levels) and therefore a significant deterioration of the current situation.
- Furthermore the closure of the Schlüsselstollen would lead to a rise of the groundwater level that would cause uncontrollable water outflows in depressions and lowlands and the weakening of soluble near-surface rocks. This would lead to a hazard or damage of existing infrastructure (roads, buildings) and to possible additional emissions of pollutants.

Deduction of Feasible and Appropriate Measures

As a result of a detailed evaluation (see internet link: PLEJADES 2013) preservation of the status quo (acquiescence) was defined as the only realisable solution. Consequently the following measures were defined for attainment of the best possible status:

- Reduction of oxygen supply to the open mine works (termination of active ventilation and closure of the remaining shafts and adits in the rear part of the mine) and therefore reduction of the potentially toxic metals loads within the framework of mine closure.
- Reduction of particle-bound mass flow using a sediment trap at the level mouth.
- Preservation of the Schlüsselstollen from the overflow point to the level mouth (about 12 km) with active maintenance to ensure everlasting drainage of the Mansfeld syncline.

Conclusions

Preservation of the Schlüsselstollen drainage tunnel in combination with termination of active ventilation and closure of remaining mine openings is the only reasonable measure which ensures a targeted and controlled drainage of the Mansfeld syncline and prevents a deterioration of the current situation. An accompanying monitoring program would help to adjust the environmental quality standards in the Schlenze and Saale Rivers.

References

WFD (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy as amended by Decision 2455/2001/EC and Directives 2008/32/EC, 2008/105/EC and 2009/31/EC.

ARGE GFE GmbH Halle / HPC-Consult (1992) Studie zu den regionalen Auswirkungen einer Aufgabe des bestehenden hydrogeologischen Niveaus des Schlüsselstollens und weiterer zutage entwässernder Stollensysteme im ehemaligen Kupferschieferbergbau der Mansfelder Mulde, Halle, 59 pp, Appendices

LHW (2012): Data basis/Methodology for mass flow calculations within the framework of the ad-hoc work group Pollutants/Sediment Management of the work group Surface Waters of the FGG Elbe, unpublished doc., (German)

PLEJADES (2012): Frachtreduzierung Schlüsselstollen, Bericht zum Arbeitspaket A: Ermittlung der Auswirkungen des Schlüsselstollens auf den partikelgebundenen Schadstofftransport in der Saale/Elbe, Magdeburg; Juli 2012 (http://www.fgg-elbe.de/hintergrunddokumente-bp2.html?file=tl_files/Downloads/EG_WRRL/hgi/hgd_bp2/Einzelstudien/Fachbericht_Frachtreduzierung_Schluesselstollen__Teil_A.pdf)

PLEJADES (2013): Frachtreduzierung Schlüsselstollen, Bericht zum Arbeitspaket B: Bewertung von technisch realisierbaren und verhältnismäßigen Maßnahmen, Magdeburg; April 2013 (http://www.fgg-elbe.de/hintergrunddokumente-bp2.html?file=tl_files/Downloads/EG_WRRL/hgi/hgd_bp2/Einzelstudien/Fachbericht_Frachtreduzierung_Schluesselstollen__Teil_B.pdf)