Flooding of the uranium mine at Königstein/Saxony – current status and monitoring conducted

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Abstract From 1984 on, at the Königstein site uranium was exclusively mined by in-situ leaching, in response to ever more decreasing ore grades. As a consequence of the applied sulfuric acid leach technology the affected geological formation exhibits a high acid potential, associated with high concentrations of easily soluble contaminants (metals, uranium included) in the mine water. In order to mitigate the environmental impact of the mine along the water pathway, remediation requires a controlled mine flooding scheme. Due to the specific hydro-geological and hydro-chemical conditions, monitoring of the groundwater quality is a key element of water monitoring at the site. The paper describes the approach of hydrochemical groundwater monitoring during mine flooding and presents solutions for representative groundwater monitoring under challenging sampling conditions in monitoring wells with depths down to 350 m below surface. The current status of mine flooding is outlined and selected monitoring results are highlighted.

Key words Uranium mining, mine flooding, Königstein mine, groundwater, monitoring

Introduction

The Königstein uranium mine is situated in an ecologically sensitive and densely populated area in the Elbe Sandstone Mountains, some 20 km southeast of Dresden, close to the Elbe river. It is classified as a typical roll-front sandstone hosted uranium deposit with an extension of about 2.5 km × 10 km (Tonndorf 2000). Workable uranium mineralization is hosted in the so-called 4th aquifer of Cenomanian age, the lowermost of four Cretaceous sandstone aquifers of the Pirna sedimentary basin (Fig. 1). The overlying Turonian 3rd aquifer, however, is classified as the region's most important local drinking water reservoir.

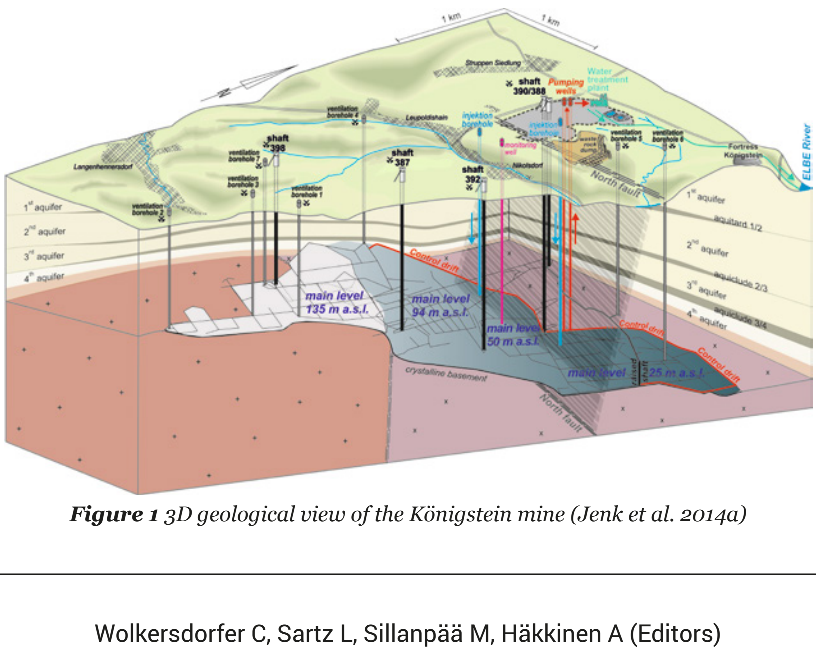

Figure 1 *3D geological view of the Königstein mine (Jenk et al. 2014a)*

Between 1967 and 1990 the deposit was exploited by SDAG Wismut, first using conventional underground mining methods. Development of the mine site extended over a surface area of approximately 6.5 km^2 and comprised four main levels (Fig. 1). In response to the ever more decreasing ore grades, from 1984 on uranium was exclusively mined by in-situ block leaching, using sulphuric acid. Production totaled some 18,000 tonnes of uranium. As of 1991, remaining resources were reported to be about 8,500 t U, including those at the unmined sub-deposits of Thürmsdorf and Pirna. In conjunction with the termination of operations by the East German uranium industry in 1990 the Königstein mine was decommissioned. Remediation activities were focused on the safe closure of the underground mine and preparation for flooding. The floodable mine voids comprised a total volume of around 2.8 million m^3. Due to the substantial quantities of sulphuric acid applied during production, mine water was strongly acid and contained very high concentrations of sulphate and easily soluble contaminants as metals and radionuclides.

With a view to minimizing environmental impacts, flooding of the Königstein mine is conducted as a controlled process with due regard to the hydraulic and hydrochemical specifics of the site. Basic elements of the controlled flooding include the system of control drifts and associated extraction wells, water injection wells, the flood water treatment unit and a licenced dump for the disposal of radioactive residues from water treatment.

For the purpose of identifying possible environmental impacts at the Königstein rehabilitation site, groundwater, seepage and surface water, discharge of treated process water, air quality and geomechanical aspects are constantly monitored.

Current above-ground groundwater monitoring

Owing to the depth of the mined deposit ranging from 150 m to 300 m below ground and to the site's hydraulic conditions, groundwater monitoring is a key element for the safe implementation of controlled flooding. Monitoring applies to aquifer #4 (Cenomanian sandstone) and in particular to aquifer #3 (Lower Turonian sandstone).

Controlled flooding of mine section I was initiated in January 2001 with open, accessible control drifts. In addition to above ground monitoring, the staged flood water rise with stoppages at the levels of 50, 80 and 110 m a.s.l. (above sea level) was accompanied by detailed underground flood water and groundwater monitoring from the accessable mine voids. This underground monitoring network comprised 31 flood water and 46 groundwater measurement points.

As from August 2009 the control drifts were flooded and hence the underground monitoring system was abandoned. Monitoring of the subsequent flood water rise from 110 m to the level of 140 m a.s.l. was performed exclusively from above ground by means of the groundwater monitoring network deployed in aquifers #3 and #4.

The measuring network for the hydrochemical monitoring of aquifers #3 and #4 comprises a total of 70 monitoring wells and has a surface extension of about 70 km^2. According to their importance and the monitoring goal, monitoring wells are divided into three categories and are sampled in different cycles:

- Basic monitoring: Widespread measuring network to monitor the general state of aquifers, sampling in a four-year cycle;
- Trend monitoring: Monitoring of mid-term changes without relevance to decision-making in the short term, sampling in a two-year cycle;
- Proximity monitoring: Monitoring of areas which, if any, are first impacted by flood water encroachment, sampling at least once a year.

Additionally, more intensive monitoring is provided to selected monitoring wells located in the proximity area where flood-induced impacts might be expected to occur at an early stage and which, for that very reason, are of particular relevance for controlling the mine flooding process during the active flooding phases. That pertains to six monitoring wells in aquifer #3 overlying the mine as well as to five monitoring wells in aquifer #4 along the northern rim. These monitoring wells are sampled in aquifer #3 in four to twelve cycles per year and in aquifer #4 biannually. Furthermore the most part of it is equipped with stationary groundwater probes to ensure continuous monitoring of water levels and electric conductivity.

The range of analyses to be performed is adapted to the relevant category of monitoring wells and does not exceed the defined parameters listed below:

- Macro constituents: TDS, filterable materials, Na, K, Mg, Ca, Fe, Fe^{2+}/Fe^{3+}, Mn, Al, Si, Cl, F, SO_4, NH_4, NO_3, NO_2, PO_4, HCO_3, (CO_3);
- Trace elements: Zn, Cu, Co, Ni, Pb, Cd, As, Ba, Sr, REE (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm Yb);
- Radionuclides: U-nat., Ra-226, range of naturally occurring radionuclides;
- Organics: TOC, AOX, Hydrocarbons.

Mine water indicators such as uranium, zinc, sulfate, cerium and neodymium in particular serve the goal of early detecting any mine water encroachment. With the aim of assessing flood water impacts on aquifer #3 indication values of these parameters were derived to apply to the 6 monitoring wells located on top of the mine (see Table 1). These indication values are based on maximum concentrations measured so far of the element under consideration plus a safety margin. This approach takes inhomogeneities in element distribution within the aquifer and effects due to changes in hydraulic conditions into consideration.

Table 1 *Indication values for flood water impact to 3rd aquifer on top of mine workings*

Parameter	Uranium [µg/L]	Zinc [µg/L]	SO_4 [mg/L]	Cerium [µg/L]	Neodymium [µg/L]
Indication value	100	300	300	20	20

In the event that exceedance of indication values has been reliably established on the basis of repeated sampling countermeasures may be taken as appropriate. Potential countermeasures also involve the lowering of the level to which the flood water has risen. Decision-making on measures to be implemented will have to consider the spatial situation and the extent of the flood water impact. To this effect, a panel has been appointed on which sit representatives of Wismut GmbH and regulators.

Technology for mobile pump sampling of deep monitoring wells

At the beginning of the 1990s, Wismut established a monitoring network of groundwater monitoring wells to monitor groundwater quality at the Königstein site. Both by their design and the materials used these wells fully comply with sampling quality standards. The wells are provided with PVC casings of an inner diameter of at least 5 inches (approximately 125 mm), and each well taps a single aquifer. Owing to the location of the monitored aquifers #3 and #4, the monitoring wells reach down to depths of 350 m and screening lengths amounted to 70 m. In particular during the initial stage of mine flooding with fully developed depression cone, depths to groundwater-levels exceeded the 200 m mark at a large number of monitoring wells.

While commercial equipment is available for representative pump sampling of groundwater monitoring wells down to depths of ca. 80 m (pump type: MP 1, manufactured by Grundfos), monitoring staff had to resort to scoop sampling for deeper aquifers still in the 1990s. However, its known from experience that data derived from scooped samples and in particular those from unexploited ground are only of limited representativity with regard to the surrounding aquifer. Reasons for this frequently include a diminished flow through from the aquifer as well as alterations of the well water induced by convective flow in the water column.

As a result of intensive development efforts, mobile equipment has become available since the early 2000s which permits representative pump sampling to be performed at all groundwater monitoring wells at the Königstein site. Mounted on trailer and truck the two units MTA200 und MTP350 (see Fig. 2) were tailored to the conditions of the site and are intended for pump sampling from two different depth ranges. The mobile units feature good cross-country mobility and by their sufficiently high and easily adjustable pumping rates they allow to comply with the hydraulic sampling criteria and to provide constant in-situ parameters. Sampling of one groundwater monitoring well is completed within one work shift (Eulenberger & Greif 2016).

Using intensive field tests during the commissioning phase of sampling equipment, adapted pumping conditions for each monitoring well were derived. With regard to optimized sampling conditions at Königstein site, a total delivery of 1.5 times of the well water content was determined for sufficient removal of altered water before taking a representative groundwater sample.

***Figure 2** Trailer mounted deep pumping unit MTA-200 (left) and deep pumping unit MTP-350 (right) during sampling operations on deep groundwater monitoring wells at the Königstein site*

Using an adjustable motor-driven submersible pump with 3 inches in diameter, the MTA200 provides pump rates of 0.5 – 1.2 m³/h with a maximum delivery head of 160 m. Centerpiece of this system is the combination of a pump cable with suspension rope inside and a nylon riser hose, both reeled onto electronic synchronized winches. This innovative design enables very short set-up/take-down times of merely 15 min and a workable handling by two operators.

Sampling unit MTP350 is suitable for delivery heads up to 320 m and covers pump rates up to 2.5 m³/h, based on a likewise adjustable 4-inches motor-driven submersible pump. Separate logging cable, pump cable and ¾-inches riser hose (20 mm) which are reeled onto hydraulic driven winches, have to be tied together by purpose-built clamps and cable clips for preventing loops inside the borehole. Therefore set-up/take-down at a 250 m deep monitoring well takes about 45 min each, using three operators. The entire system is mounted on cross country truck with box body divided in lab unit (front) for sample preparation and utility section at the rear part.

Results

Controlled flooding of mine section I was initiated in January 2001 with open control drifts. At that time, flood water was collected in basins below ground by means of an elaborate drainage adits and galleries system and subsequently – separately from uncontaminated groundwater – pumped via main shafts #388/390 to the surface for treatment.

Since control drifts were flooded mine flood water is pumped from the control drift system which acts as a horizontal well. For this purpose, extraction wells A' and B were drilled north of shafts #388/390 and linked by chambers to the northern control drift. With control drifts henceforth flooded, the rise of the flood water level was resumed in April 2011 and lasted until January 2013 when the final level of 139.5 m a.s.l. was reached. At this currently maintained flood water level of maximum 140 m a.s.l., permitted in section I, the total fill volume of mine voids and replenishable pore volume in cretaceous sandstone has been identified amounting to a total of about 7 million m³ of water (Jenk et al. 2014b).

The mine flooding process was reliably surveilled by comprehensive monitoring of groundwater measuring points deployed both underground and above ground. At the same time, a reliable data base was established for an assessment of the flooding process. Data recorded during the final flood water rise from 110 to 140 m a.s.l. (from 04/2011 through to 01/2013) document in particular that the exclusively remained above ground deployed groundwater monitoring network is capable of detecting an impact of the mine flooding on the surrounding groundwater. Custom-built mobile pumping equipment allows representative sampling of the site's deeper-than-average groundwater monitoring wells for reliable monitoring of groundwater quality from above ground.

Down to the present day, the acquired monitoring data allow to safely exclude any impact downstream of aquifers #3 and #4 caused by encroaching flood water. This is exemplified by uranium concentrations recorded during the period of flood water rise from the level of 110 to 140 m a.s.l. and during the current stoppage from groundwater measuring points within the aquifer #3 on top of the mine (see Fig. 3).

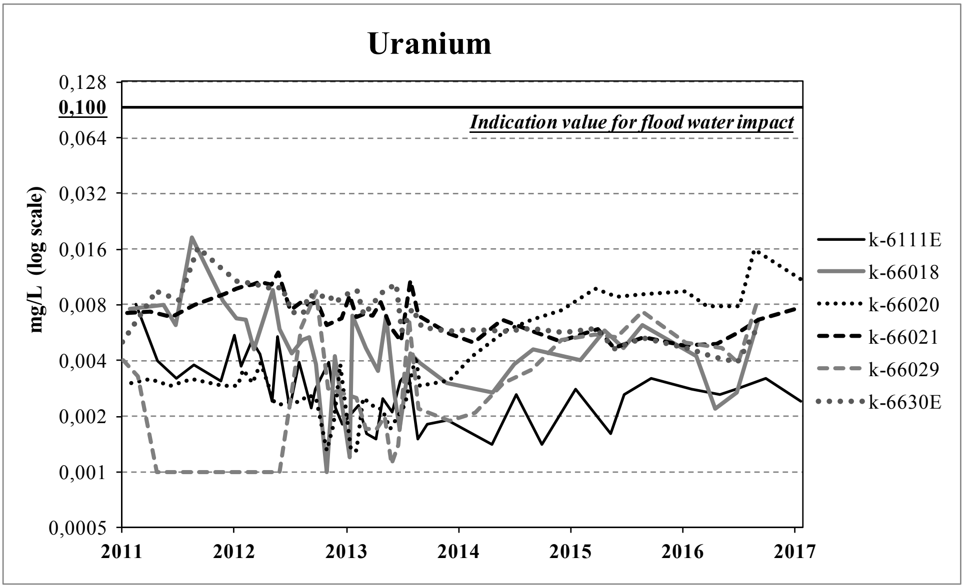

Figure 3 *Uranium concentrations in monitoring wells in aquifer #3 on top of the mine since 2011*

Outlook

Owing to the natural inflow of groundwater, pumping the flood water via extraction wells is imperative for maintaining the current flood water table of about 139.5 m a.s.l. and can be terminated only if a natural flood level of approximately 200 m a.s.l. is achieved. Flooding of mine section II is aimed at the recovery of these hydraulic conditions which prevailed prior to mine development.

Considering the absence of a sustainable alternative technical solution solely a final flooding would enable a complete and conclusive remediation of the site. Unavoidably linked with limited emissions of pollutants into the surrounding aquifers, the permitting procedure for this flooding step, initiated in December 2011, is still pending. A new approach to push the flooding progress is the definition of an observation and control area for a spatial limited encroachment of the surrounding aquifers #4 and #3. This area is framed by the contour of the existing mining concession and an already granted pollution-rim of the aquifer #4. Currently, technical discussions with respect to potential scenarios and connected risks with the relevant authorities are conducted. As a result, a permit application for a hydraulic test was submitted in March 2017 to obtain basic data for better prediction of the hydrological and geochemical conditions in consequence of a further flooding.

The Königstein site is equipped with a groundwater monitoring system which ensures both the current and future secure monitoring of mine flooding. Depending on regulatory framework conditions yet to be put in concrete terms for the implementation of flooding section II of the Königstein mine, occasional amendments to the existing measuring network might become necessary.

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