Final Flooding of the Königstein Uranium Mine - Supporting Activities and Implications for Monitoring

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Abstract

Between 1967 and 1990, the SDAG Wismut mined about 18,000 t of uranium at the Königstein site. The deposit, located very near a national park, is hosted in a Cretaceous sandstone formation at depths from 150 to 300 m below the surface. Since 1991, the combined effects of conventional underground mining followed by in situ leaching are being rehabilitated. As a result of the applied sulfuric acid leaching, the affected geological formation displays a high acidification potential, and high concentrations of dissolved contaminants as U, As and Zn in the associated mine water. Adaptions to the existing elaborate water monitoring network are required as the intended stepwise flooding is accompanied by hydraulic and hydrochemical tests. This paper outlines the current status of mine flooding at the Königstein site. The intense groundwater monitoring carried out during the first hydraulic test and its main results are described, along with approaches to adapt the monitoring network for a second hydraulic test.

Keywords: Uranium mining, Mine flooding, Groundwater monitoring, Königstein mine

Introduction

The Königstein uranium deposit is situated in the Elbe Sandstone Mountains, about 30 km southeast of Dresden, near the Elbe River. Classified as a typical roll-front sandstone hosted uranium deposit, it covers an area of about 2.5 km × 10 km (Tonndorf 2000). It is hosted in the lowermost of four Cretaceous sandstone aquifers of the Pirna sediment basin (Fig. 1), where profitable uranium mineralization is associated with the so-called 4th aquifer of Cenomanian age. Its location in the Saxon Switzerland National Park combined with the fact that the overlying 3rd aquifer is considered the region's most important drinking water reservoir makes the remediation extremely challenging.

The Königstein uranium deposit was mined between 1967 and 1984 by means of conventional mining methods. Due to decreasing yields, the mining strategy shifted towards in–situ leach mining using sulphuric acid as the solvent. By this process, some 130,000 t of acid were used in the underground, inducing consecutive reactions due to the oxidation of pyrite and the dissolution of metals and radionuclides over an area of about 6 km^2. When decommissioned in 1990 in association with the German Reunification, a total of about 18,000 metric tons of uranium had been produced from the Königstein mine. However, regions such as the Thürmsdorf and Pirna sub-deposits remained unmined and still exhibit a high contamination potential.

Controlled flooding of mine section I up to the permitted water level of 140 m above sea level (a.s.l.) was completed in 2013. Basic elements of controlled flooding and the safe holding of the current water level include the system of control drifts and two connected extraction wells (FBL Aneu and FBL B), a water treatment plant, two injection boreholes for treated and potable water, and a waste dump for the disposal of radioactive residues. The applied remediation strategy of pump-and-treat significantly decreased the metals and radionuclides in the mine water during the past three decades. However, the contamination potential remains high. In 2021, the mean mine water composition was characterized by a pH of 3.1, SO_4 = 800 mg/L, Fe = 38 mg/lL, U = 6.5 mg/L, Zn = 8.4 mg/L, and Ra-226 = 5.5 Bq/L.

As the technology of pumping, cleaning and reinjection led to decreasing

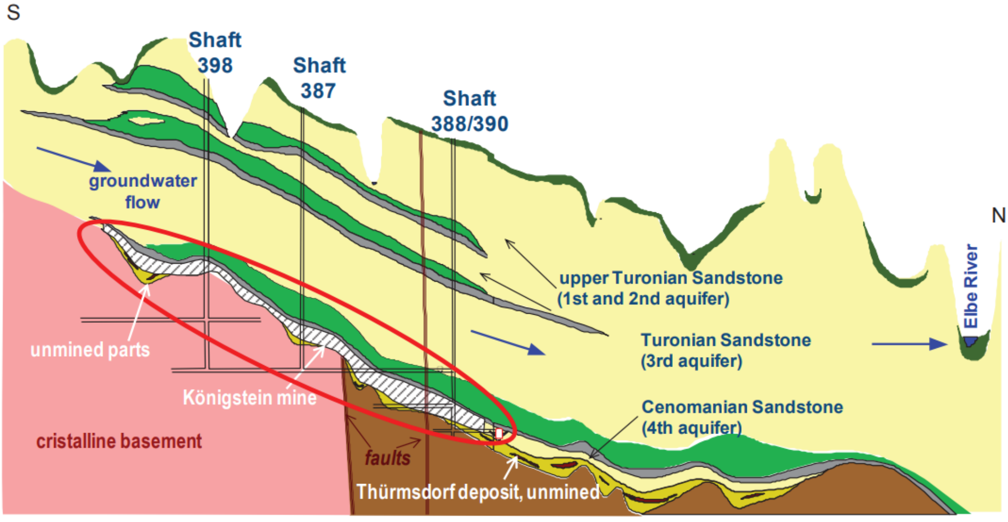

Figure 1 Geological cross section of the Königstein mine site (Frenzel et al. *2016)*

concentrations of sulphate, metals and uranium, treatment methods had to be fundamentally adapted. Especially, the separation of uranium as a by-product of mine water treatment could not be maintained at reasonable costs and was shut down. The processing and treatment facility for mine water was converted to solely applying a lime treatment and precipitation technology, whereby the total residues are stored in the Schüsselgrund waste dump nearby. While the flood water level is currently kept stable below 140 m a.s.l., the water monitoring continues: groundwater observation in four aquifers, at the surface, seepage water, and the discharge of treated mine water into the Elbe River.

Preparing measures for final flooding – hydraulic test I

To gain field data for making reliable forecasts on the hydraulic and hydrochemical consequences of further mine flooding, a hydraulic test was performed from 2017 to 2018. It involved the controlled lifting of the flooding level up to 150 m a.s.l., followed by its immediate return to the initial level of 140 m a.s.l. During lifting, which lasted about 6 months, about 250 m^3/h of treated water was injected into the mine. The initial water level was reached within 3 months after stopping the injection. During the hydraulic test, the flooding level was controlled in such a way that passage of mine water into aquifer #4 could be excluded at any time. A limited mine water encroachment into aquifer #3 was expected during the test in the area of the main hydraulic weak zones, which include the hydraulically active north fault and the area of the former ventilation borehole #6.

Hydraulic test I was accompanied by a response plan, which basically had been applied also for flooding of mine section I. The main objective of the response plan was to assure a concentration limit of ≤30 µg/L of U outside the boundary of a so-called observation and reaction area (O&RA). The shape of this O&RA results from the border of mining permit at the Königstein site and an already approved impact-limit of about 500 m downstream of mine voids. To assess the effect of the flood water on aquifer #3, indication values for the typical mine water indicators U, Zn, SO4, Ce and Nd were derived (Table 1) and appropriate countermeasures were defined to limit the potential of mine water encroachment. These countermeasures also involved lowering of the flood water level.

Hydraulic test I was performed using the existing monitoring network from flooding section I. The test was accompanied by an intensified monitoring program for the early detection of mine water encroachment to aquifer #3. Sampling frequencies and water

Table 1 Indication values defined in the response plan for groundwater in aquifer #3 inside the observation and reaction area (in brackets: outside the observation and reaction area)

Parameter	U [mg/L]	Zn [mg/L]	SO4 [mg/L]	Ce [µg/L]	Nd [µg/L]
Indication value	0.1 (0.03)	0.3	300	20	20

level measurements at monitoring wells were increased according to their function in the monitoring network (Table 2). In order to observe possible long-term influences on the groundwater quality, the intensified monitoring was maintained for one year after finishing the hydraulic test. The test was accompanied by a long-term pumping test at monitoring well k 66021 in aquifer #3, which is located about 50 m downstream the north fault (Fig. 2). The goal of the pumping test was to activate the groundwater flow towards the well by the permanent pointwise water abstraction. Hence, it served for the earlier and more reliable detection of a possible local passage of mine water to aquifer #3.

Monitoring by means of sampling in aquifer #4 along the mine contour wasn't intensified, as passage of mine water from the control drift system was not expected as long as the water depression in the control drift was retained by a constant pumping of at least 250 m^3/h from the extraction wells.

Generally, sampling from monitoring wells took place by pumping with two custom-made sampling units, MTA-200

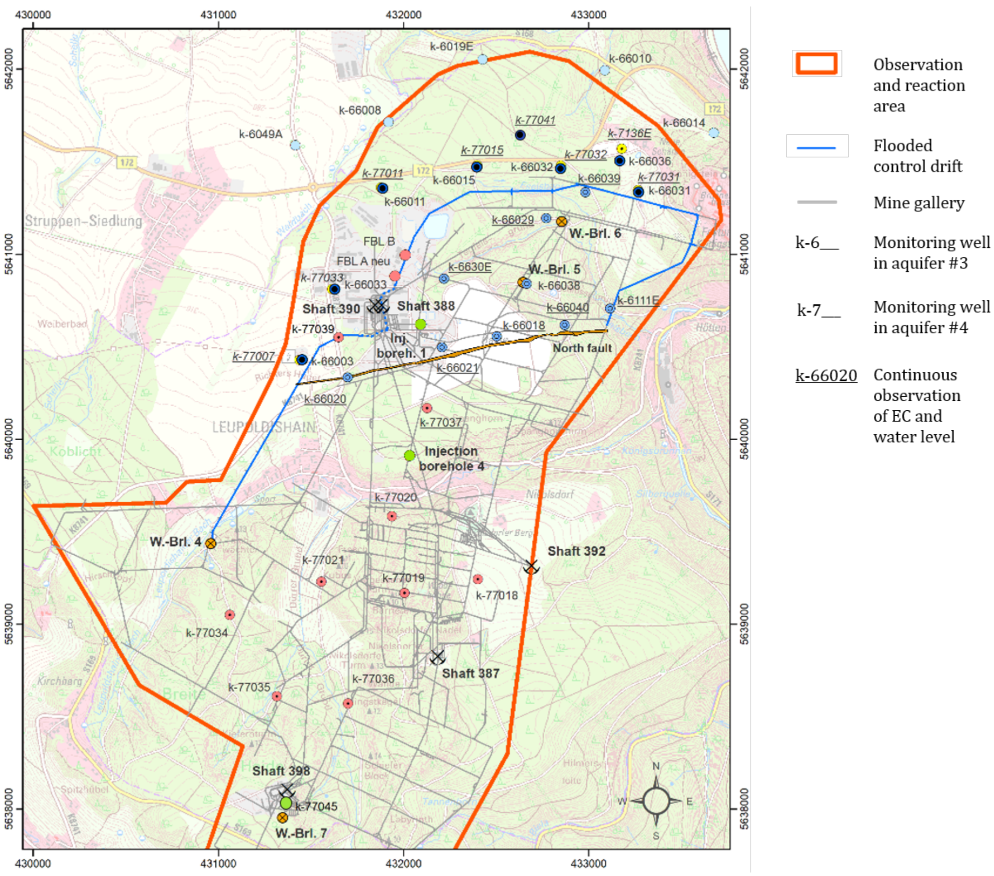

Figure 2 Groundwater monitoring network in the aquifers #3 and #4 at the Königstein site

Table 2 Intensification of hydraulic and hydrochemical monitoring in aquifer #3 for the first hydraulic test 2017-2018 (frequency of regular monitoring in brackets)

Category	Monitoring well	Monitoring during hydraulic test I
Northern field above the mine	k-6111E, k-66018, k-66029, k-66038	EC + water level = continuously Sampling = 12x/a (4x/a)
	k-66020, k-6630E, k-66032, k-66036	Sampling = 4x/a
	k-66021 - long-term pumping test	In-situ-Parameter = 3x/week Sampling = biweekly

and MTP-350, allowing pump sampling to a depth of 350 m (see Eulenberger *et al.* 2017 for a detailed description). For every monitoring well, a specific pumping regime was developed over the years based on its construction depth, hydraulic conductivity, geophysical characteristics and diameter. Hence, technical pumping parameters such as pumping time, flow rate and sampling depth were specific for each monitoring well but were kept constant so as to guarantee comparable results over time.

The results of hydrochemical monitoring during and after the first hydraulic test provided no indication of any influence on the water quality of aquifers #3 and #4. Concentrations of typical mine water parameters U and Zn showed no significant increase in response to the temporary rise of the flood water level, and the indication values of mine water influence for U and Zn were not exceeded (Fig. 3); SO4 and the rare earth elements behaved similarly. These results substantiate the decision for a second hydraulic test in which the elevated floodwater level is to be maintained for a longer period. In this test, monitoring in aquifer #3 does not have to be intensified a priori, but a case-dependent increase of sampling frequency on affected monitoring wells will be carried out.

Preparing measures for final flooding - hydrochemical field test

From 2020–2021, a hydrochemical field test was performed at the Königstein site. The single borehole test was carried out at an existing monitoring well in the mine (k-77018), which was selected according to its suitability concerning groundwater flow and chemical composition. During the test, a reactive fluid consisting of potassium hydroxide and butanol was injected directly

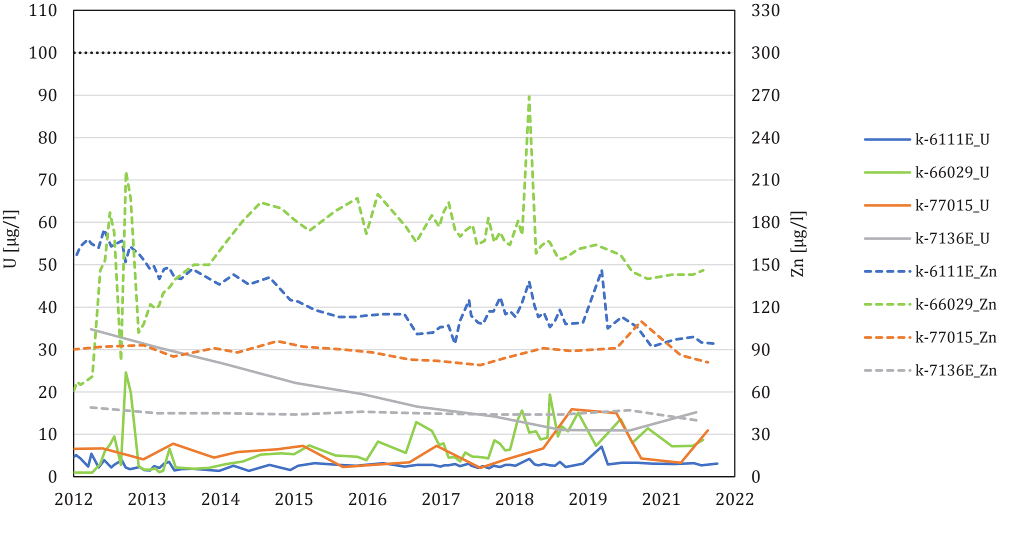

***Figure 3** Uranium and zinc concentrations in aquifers #3 (k-6111E, k-66029) and #4 (k-77015, k-7136E) above the mine since 2012 (dotted line: indication values for mine water influence)*

into the well, and re-pumped after a reaction time of 1–2 weeks. Over a period of 8 months, a total of 17 injections took place, followed by a two-month monitoring phase.

The hydrochemical field test proved the suitability of the utilized reactive fluid to effectively reduce the acidic potential of the mine water and enhance bacterial sulphate reduction. After a lag-time of about two months, the decrease of iron along with the rise of sulphide, TOC, and metabolic products of carbon acids verified the increased local microbial activity in the mine water (Bilek *et al.* 2021).

Adaption of monitoring to further flooding steps

Currently, preparations for the implementation of a second hydraulic test are in progress. In contrast to hydraulic test I, the elevated water level of 150 m a.s.l. level will be kept constant for several years. The main goal is to gain data for the verification, adaption and improvement of the existing hydraulic and hydrochemical model of the Königstein mine. An essential component of hydraulic test II is the injection of reactive fluids directly into the upstream, southern part of the mine by means of a borehole specially drilled for that purpose.

Hydraulic test II is accompanied by a monitoring program, which largely corresponds to the existing program with some adaptions, including the option of intensifying it. Criteria for an event-related intensification of monitoring, the initiation of measures for limiting negative influences and, ultimately, the termination of the test are defined in a response plan, which aims at reliable observance of ≤30 µg/L of U outside the O&RA in aquifer #3. According to the response plan, two criteria are defined for intensifying the sampling frequency in an affected monitoring well: the increase in EC (>100 µS/cm) or the excess of indication values (Table 1) in a monitoring well. The continuous observation of the electric conductivity in the water of the aquifers #3 and #4 with probes (SEBA Hydrometrie) plays an important role for the early detection of encroaching mine water. For that purpose, all existing permanent probes will be equipped with transmission modules to perform data transfer using a local wireless network (LoRaWAN). This enables the instant detection of changes in conductivity and subsequently a quick decision on additional monitoring activities as well as further measures to limit floodwater impacts.

Stepwise extension of the monitoring network for final flooding

In order to prevent environmental damage to the surrounding aquifers and to identify negative influences from flooding in time, the regulatory requirements are exceptionally high for the monitoring that accompanies the whole process of flooding (Eulenberger *et al.* 2021). That's why the existing monitoring system in Königstein is planned to be extended stepwise with monitoring wells, injection wells, and, if needed, further extraction wells, in accordance with the strategy of mine flooding. Monitoring wells in aquifers #3 and #4 serve for the early detection of mine water encroaching from the mine to the surrounding aquifers. An early detection of encroaching mine water requires the intensified observation, especially in areas of critical mine water encroachment, and protection of the aquifer outside the O&RA. Further, the results of geological and chemical analyses gained from the sampling water and drilling cores will serve to enhance the data bases used for runoff and transport modelling at the former mining site. The selection of appropriate sites for new monitoring wells bases, besides the findings from monitoring and modelling, on the documentation of hydraulic weak zones in the aquiclude between aquifers #3 and #4, that existed during active mining and could not be sealed completely (Frenzel *et al.* 2018). The construction of injection wells is planned in order to enable the injection of neutralizing, reactive fluids into the mine body to enhance the in-situ remediation. The need for a further extraction well could arise from a changing hydraulic conductivity or hydraulic connection of the control drift system and, in consequence, the failure of the current mine water management (Eulenberger *et al.* 2021). The strategy of stepwise extension of the monitoring network, depending on further gains in knowledge, is due to the high construction costs of groundwater monitoring wells at the Königstein site, resulting mainly from the great depth of aquifers as well as the need for hydraulic sealing of the overlying aquifers. In total, eight additional monitoring wells in the northern part of the former mine (k-66039, k-66040, k-77039: installed since 2018; k-77041: in construction) and six injection boreholes (k-77045: in construction), spread over the entire former mine area, are planned with depths up to 300 m (Fig. 2).

Outlook

The complete flooding of the Königstein uranium mine from the current water table of 140 m a.s.l. to the natural level of about 200 m a.s.l. remains a long-term process lasting several decades. The experience and output gained from hydraulic test I and the hydrochemical field test make a valuable contribution to our understanding of the complex hydraulic and hydrochemical system of the Königstein mine and provide important prerequisites for final flooding. The existing monitoring network forms a solid base for further steps towards the complete recovery of pre-mining conditions. The stepwise expansion of monitoring wells at carefully selected locations is a compromise between the need to fill gaps and opportunities to minimize expenses and efforts for the costly and time-consuming construction and running of new monitoring wells. The observation of hydrochemical and hydraulic changes caused by the rising flood water level require the short-time adaption of monitoring by the shortening of sampling frequencies and increasing the scope of analysis. These facts are a major challenge concerning monitoring accompanying final flooding of the Königstein uranium mine.

The extended monitoring network, including additional technical equipment (probes with LoRaWAN, appropriate and sufficient sampling equipment) along with supporting measures (response plan) for the quick detection of the influence of flood water, are important for minimizing the possible environmental impacts and to finally ensure the safe flooding of the Königstein mine.

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