Implementation of Operative Monitoring During Flooding of the Königstein Mine – First Experiences from Hydraulic Test 2

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Abstract

At the Königstein site, final flooding of the former uranium mine is taking place according to a stepwise flooding concept. The process is accompanied by an intensive, site-specific monitoring program, which is subject to continuous adaptation and optimization as remediation progresses. In preparation for flooding beyond 140 m a.s.l., the existing monitoring system was extended by the construction of new wells as well as equipping permanent probes with wireless network modules for continuous transmission of water level and EC. This paper discusses first outcomes from adapted monitoring and provides an overview of the current state of flooding.

Keywords: Mine flooding, uranium mining, groundwater monitoring, Königstein mine

Introduction

Situated inside the Elbe Sandstone Mountains and surrounded by important groundwater resources, the Königstein uranium deposit is located in the lowermost of four cretaceous sandstone aquifers within the Pirna sedimentary basin. About 6 km² of the total 25 km² uranium deposit were subject to mining activities by the former Wismut SDAG. Due to decreasing uranium grades in the mineralized sedimentary rock, conventional mining shifted towards an underground in situ block leaching technology in 1984. In total, some 130,000 t of sulfuric acid were brought into the mine until mine closure due to the German reunification in 1990. By this process, more than 50 million tons of sandstone came into contact with the acid, triggering follow-up reactions as the release of easily soluble contaminants as metals and radionuclides (Jenk *et al.* 2011).

Following a longstanding and thorough phase of preparation, stepwise controlled flooding of the mine was initiated in 2001. The basic principle is to reduce leachate-related pollutants in the mine whilst ensuring the greatest possible protection of the surrounding aquifer areas (aquifers #3 and #4). Main elements of flood control are two extraction wells (FBL), which are connected to the northernmost and deepest mine workings, the so-called control drifts, which have no direct connection to the remaining mine by open mine workings or boreholes (Figure 1). By these wells, the contaminated water is pumped from the mine, cleaned in the treatment plant on site, and finally discharged into the river Elbe or re-injected into the mine. Continuous pumping of the flooding water maintains a hydraulic gradient from the host sandstone towards the control drift and prevents acidic flooding water from flowing into the surrounding aquifer #4. Controlled flooding of mine section I until the water level of 140 m a.s.l. was completed in 2013.

Although the applied remediation technology of pump and treat led to a major decrease of acid and radionuclide concentrations during the last three decades, contamination potential persists at a high level. In 2025, the extracted mine water had a pH of 3.3 and was characterized by average concentrations of SO4 = 620 mg/L, Fe = 39 mg/L, U = 6.3 mg/L, Zn = 4.2 mg/L and Ra 226 = 6.5 Bq/L.

Stepwise permanent flooding above the level of 140 m a.s.l. was preceded by years of planning and preparation. During this time, several large-scale tests were conducted, the findings of which served to further develop the hydraulic and hydrochemical models.

Specifically, since 2017, the following measures and tests have been carried out as prerequisites to continue the final flooding above 140 m a.s.l. in form of the so called "hydraulic test 2":

- Hydraulic test 1: It involved a controlled short term flooding to a level of 150 m a.s.l., which took about 6 months, followed by immediate return to the initial level of 140 m a.s.l.. The test was accompanied by an intensified monitoring program for the early detection of mine water encroaching into the upper aquifer #3. The results of hydrochemical monitoring during and after the test provided no indication of mine water influence on the water quality of the surrounding aquifers #3 and #4 (Frenzel *et al.* 2018, Schmidt *et al.* 2022)
- Hydrochemical field test: In 2020, a single borehole test was carried out at an existing monitoring well (k-77018) in the mine. Over a period of eight months, a reactive solution consisting of potassium hydroxide and butanol was injected directly into the mine (17 times in total) and re-pumped after a reaction time of 1–2 weeks. Analyses of the extracted water effectively demonstrated the suitability of the reactive solution for an efficient reduction of the acid potential. After approximately two months, decreasing iron concentrations and an increase in sulfide indicated enhanced bacterial sulfate reduction in the vicinity of the test well (Bilek *et al.* 2023).
- Construction of an injection borehole in the southern part of the mine: For the implementation of supporting measures for acid reduction and contaminant precipitation in the mine using reactive solutions, a strategically located injection borehole (k-77045) was drilled into upstream open mine voids near the sealed shaft 398 in 2023 (see Figure 1).

In contrast to hydraulic test 1, in hydraulic test 2 the water level in the former mine is plan-ned to be kept at the target level of 150 m a.s.l. for at least two years. Flooding is accompanied by the injection of reactive solutions directly in-to the mine. Hydraulic test 2 started in Mai 2024 with the first injection of NaOH at k 77045, one year later lifting of the mine water level began. If the current operation is maintained, the tar-get level of 150 m a.s.l. will be reached in late summer 2026.

Adaption of the monitoring network to further flooding steps

The existing monitoring network, consisting of approximately 140 groundwater monitoring wells in the 3rd and 4th aquifers, was designed to reliably monitor any effects of mine flooding at least to a level of 140 m a.s.l. To accommodate higher water levels beyond this, the monitoring network was gradually expanded starting in 2018.

The construction of new monitoring wells for flooding beyond 140 m a.s.l. mainly serves for supervising potential mine water encroachments in the vicinity of incompletely backfilled ventilation shafts (k-66039) and along the north fault (k-66040), as well as monitoring of potential contaminant mobilisation from the unmined uranium deposit Thürmsdorf (k-77041). Thereby, the exact location of a planned monitoring well depends not only on the geological conditions underground and their position downstream of potential locations of mine water encroachment, but also on surface factors such as accessibility and land ownership. The extension is done step by step, in accordance with the flooding strategy and based on the latest findings, in order to account for high installation costs due to the great depth and the need for hydraulic sealing of overlying aquifers. Groundwater monitoring wells and injection boreholes required to expand the monitoring network for further flooding, which have already been constructed or are currently under construction, are listed in Table 1.

New measuring points are used for collecting water samples in order to expand and improve the data basis for site-specific downstream and transport models (Eulenberger *et al.* 2021). At the same time, core material obtained from the boreholes is used to carry out for example column tests to investigate the reaction of unmined ore horizons to the inflow of acidic mine water.

A further expansion of the measurement network is also planned for the further

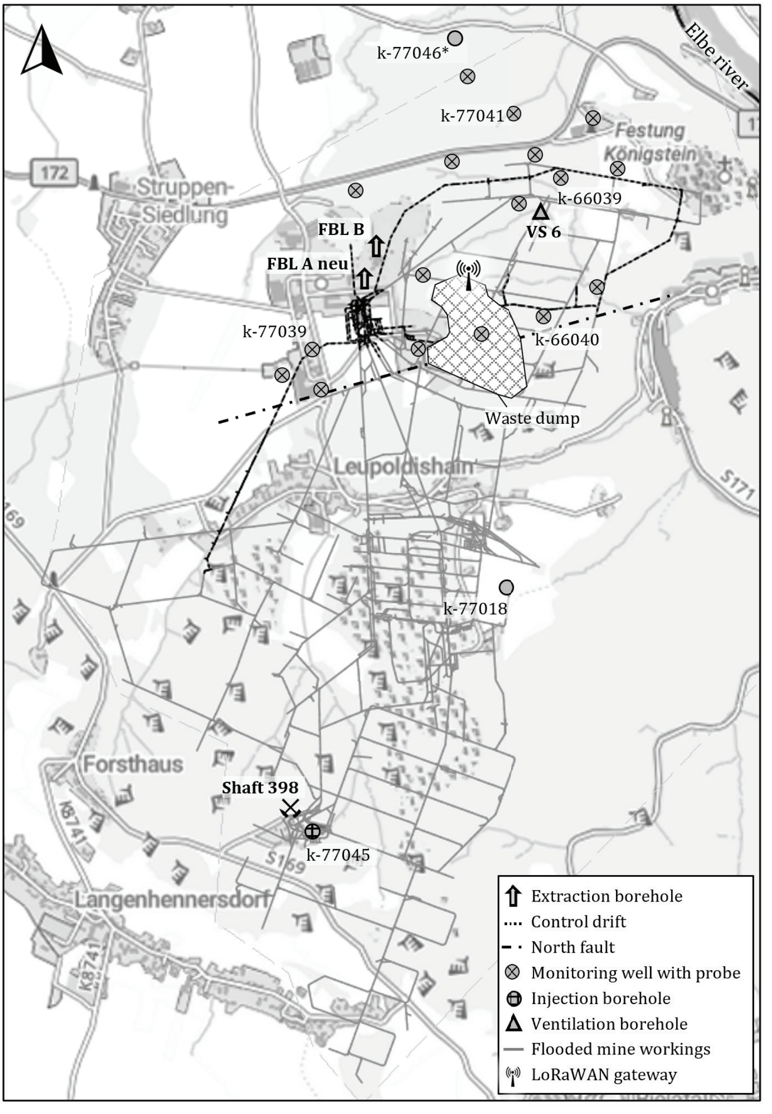


Figure 1 *Map of the Königstein uranium mine with relevant elements discussed in this paper.*

Table 1 *Overview of monitoring wells build in recent years for the stepwise extension of the monitoring network for the adaption to further flooding of the Königstein mine.*

Monitoring well	Aquifer	Year of construction	Depth	Function
k-66039	#3	2018	200	Monitoring downstream of ventilation shaft
k-66040	#3	2020	192	Monitoring along north fault
k-77039	mine	2022	283	Monitoring the hydraulic connection of control drifts north and west
k-77041	#4	2024	273	Monitoring of unmined deposit
k-77045	mine	2023	259	Injection of reactive fluids into the mine
k-77046	#4	2026	272*	Monitoring of unmined deposit

* planned depth

progress of flooding. The necessity and exact positioning of the measuring points to be established will be determined by the findings gained from the flooding process in the coming years. The evolving flooding strategy sets the framework for the gradual expansion of the current measurement network.

Using electrical conductivity as early indicator for mine water influence

Criteria for event-related intensification of monitoring, for initiating measures to limit the spread of hydrochemical influence, and ultimately for the termination of hydraulic test 2 are defined in a response plan. The response plan specifies an increase in EC of 100 µS/cm over a period of one month, measured by probe or sampling in wells of aquifer #3, as a criterion for the intensification of sampling. In a first step, an additional sample will be taken for verification, followed by monthly sampling and the comparison with indicator values which have been specified in the response plan for indicating an influence from flooding water.

The electrical conductivity is continuously observed using permanent probes (*SEBA Hydrometrie*) in 17 monitoring wells of aquifers #3 and #4. The mine waters EC is approximately 1.5 mS/cm, which is about 10 times that of regional unaffected, low mineralized groundwater, so that the possible influence of mine water but also secondary processes can be detected at an early stage.

During flooding up to 140 m a.s.l. and the subsequent holding of the water level, permanent probes were read at regular intervals of 2-4 weeks and data were uploaded to the environmental database for evaluation. To ensure an instant detection of changes in electrical conductivity in the monitoring wells of aquifers #3 and #4 during hydraulic test 2, online data transmission was established. Due to unfavorable local conditions in mountainous terrain and with dense forestation, reliable mobile network coverage is limited in the Königstein region. Therefore, a local wireless network based on LoRaWAN technology was installed. LoRaWAN (=long range wide area network) is a network protocol designed for the wireless connection of battery-operated devices to the internet. Being independent from the mobile network and having a very low power consumption, it is possible to transmit small amounts of data over long distances, which is why the technology is very suitable for use in remote areas.

The path taken by the probe data from the measurement on-site via online transmission into the process control system to the final presentation in the environmental database is shown in figure 2. The process control system of Königstein, where all data are collected, performs an initial valuation of transmitted data. Failures in data transmission, increases in EC and potential differences compared to the control drift trigger an automated notification of the staff responsible. Following the ongoing transfer of data from the process control system to the probe database, the data is validated and approved, and finally transferred to the environmental database.

In 2022/2023, the LoRaWAN technology was tested at the Königstein site over a period of one year as part of a feasibility study. It

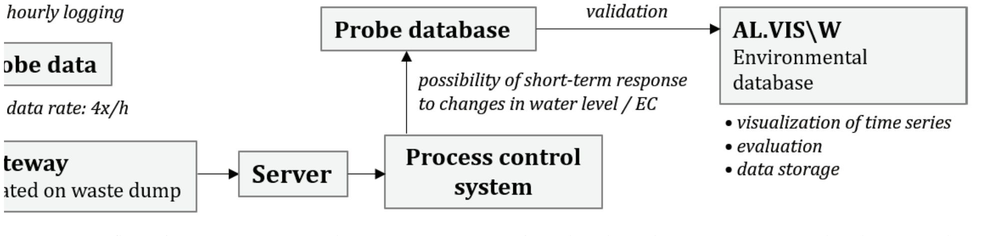


Figure 2 Dataflow for continuous online transmission of probe data by LoRaWAN technology at the Königstein site.

revealed that all measuring points to be equipped could be reached via the wireless network standard if the gateway was located on the northeastern edge of the former mine operating area (Figure 1). During the test period, it was also observed that the transmission rate highly depends on external factors. For example, precipitation leads to a substantial reduction in the transmission rate. Generally, transmission rate is clearly better in winter, due to the lack of foliage on the trees, high cloud cover, and snow- or ice-covered surfaces, which promote the reflection of radio waves and thus signal transmission. Due to the positive results of the feasibility study, all existing permanent probes observing the aquifers #3 and #4 were equipped with LoRaWAN transmission modules prior to the beginning of hydraulic test 2.

After more than one year of operating the technology at the Königstein site, it has been shown that the principle works reliably at over 90% of the monitoring wells equipped with probes. Depending on the weather, minor data gaps of few hours may occur, which are acceptable due to change dynamics of the measured parameters. At few monitoring wells, due to their location and position (underfloor, situated in a valley), data transmission is unreliable and insufficient, with data gaps of up to several days. Therefore, manual probe readout remains necessary at these locations. Measurable reactions related to the beginning of hydraulic test 2 were evident after few months of rising the flood level. The following section describes the observations made at the affected monitoring well k-66040 in more detail and explains the derived steps.

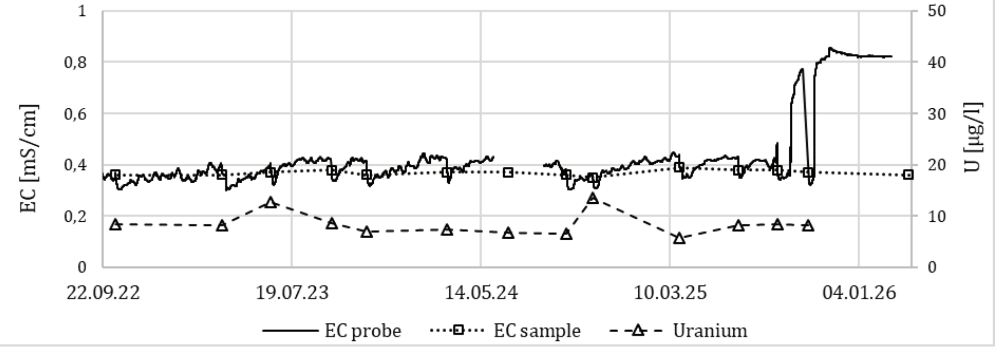
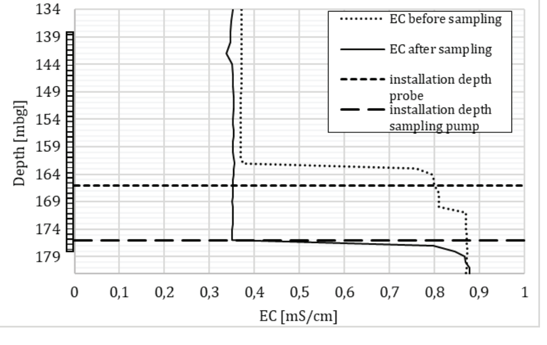


Figure 3 EC profile measured at monitoring well k-66040 using a permanent probe compared to EC and uranium values in pumped samples.



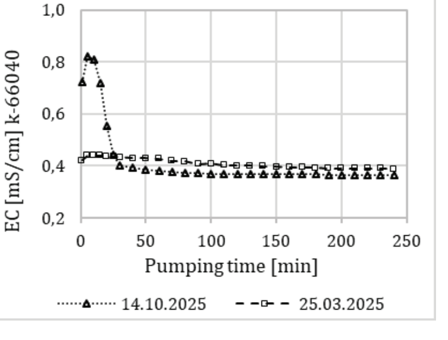


Figure 4 EC depth profile of k-66040 from October 9, 2025 - before sampling, compared to October 15, 2025 after sampling (left); EC profiles of k-66040 measured during pumping prior to sampling (right).

After its construction in 2020, the water in the monitoring well k-66040, which exposes the Lower Turonian sandstone of aquifer #3 at a depth of 90 to 180 m, had a total mineralization of 230 mg/L, with a slightly acidic environment (pH 6). The concentrations of mine water typical parameters were considerably below background values in this region, thus showing no influence by mine water. In September 2025, a sudden increase in EC to 0.7 mS/cm occurred, with a maximum of 0.85 mS/cm finally (see figure 3). Representative sampling at the monitoring well is carried out by pumping once the borehole water has been removed and in-situ parameters (EC, pH, temp.) in the pumped water have stabilised. Figure 3 shows that, for all samples taken in this way, the electrical conductivity remained at a consistently low level, and also uranium showed no upward trend.

Electrical conductivity profiles recorded, using a cable-based light probe with EC sensor (*Hydrotechnik GmbH*), a few days before and after sampling in October 2025 showed that there is a clear stratification in the monitoring well with a higher mineralized layer underlying the typical low mineralized groundwater. The interface level was lowered by 14 m due to sampling (Fig. 4, left). The continuous EC measurements taken during the pumping process prior to sampling showed that the volume of higher mineralized water was completely pumped out at a pumping rate of 2.0 m^3/h within less than 30 minutes (Fig. 4, right). This equals to a maximum volume of 1 m^3 of higher mineralized water. The results of water analyses also remained unchanged compared to the initial values with regard to parameters typical for floodwater. Results thus indicate that the upwelling water with higher EC is not representative for the hydrochemical character of the surrounding aquifer. The change in pressure conditions, and thus altered hydraulics caused by raising the water level during the hydraulic test 2, leads to a changing convection within the monitoring well. Hence, a direct inflow of mine water cannot be assumed so far, based on the available results. A similar effect was also observed after hydraulic test 1. As long as the volume of higher mineralized water can be completely pumped out within short time during the sampling process and chemical analysis shows no abnormalities, an encroachment of mine water to aquifer #3 along the north fault is not to be assumed.

Conclusions

The permitted increase in water level during hydraulic test 2 as part of the complete flooding of the Königstein mine is in progress and accompanied by an intensive monitoring program. Initial hydrochemical effects can be observed at surrounding groundwater monitoring wells. It became evident, that the transmission of probe data via LoRaWAN technology is well suited for the early detection of hydrochemical changes in remote areas. Investigations of initial changes at monitoring wells show, that an increase in the electrical conductivity does not necessarily indicate mine water influence, but rather that the causes can be multifaceted and complex. Conducting supplementary investigations, such as creating electrical conductivity profiles and intensifying sampling, can provide insights into the relevant reactions in the aquifer, and provides data for further hydraulic and hydrochemical modelling. Hydrochemical signals during the process of mine flooding should therefore not only be viewed as a problem regarding the risks to the surrounding aquifer. They also essentially contribute to validating and further developing the model assumptions for predictions and optimization of further flooding steps.

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