Remediation of the uranium ISL-site Königstein/Germany

ARD Mitigation measures and results

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Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Structure of Presentation

- Overview Wismut's remediation programme
- Introduction into Königstein ISL-site
- Remediation tasks and strategy
- Field-scale ARD mitigation measures
  - Immobilisation of leaching blocks
  - Field Test with injection of alkaline solutions
  - Hydraulic Test 1
  - Hydrochemical Test
  - upcoming Hydraulic Test 2
- Conclusions and perspectives

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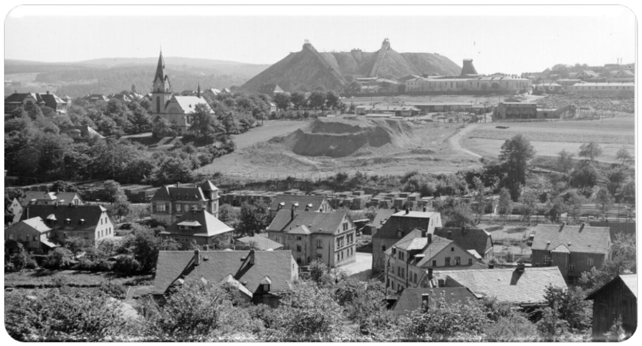
Uranium mining in Eastern Germany - History of the company Wismut

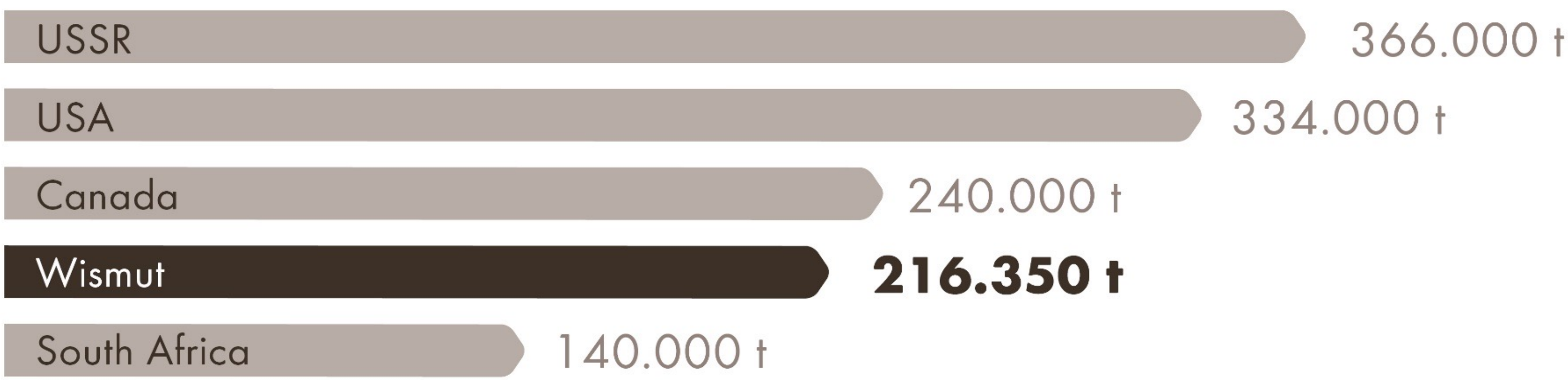


1946 Start of Uranium mining under supervision of Soviet military

1954 Bi-national Soviet-German company (SDAG) WISMUT

1990 End of uranium mining as a result of reunification

Total production: 216,000 t U



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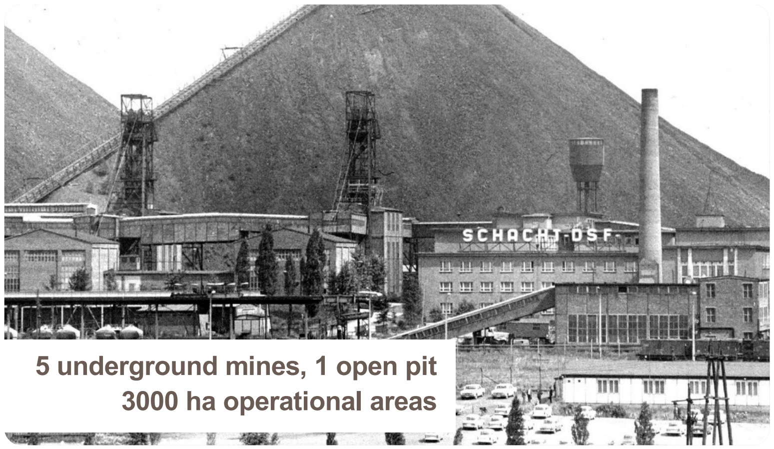
Situation at termination of uranium mining by Wismut 1990/91



5 underground mines, 1 open pit
3000 ha operational areas

48 waste rock dumps
310 million m³

2 uranium mills, 75 ha operational area

4 Tailings ponds, 570 ha, 160 million t

Transformation and Remediation of Uranium mining sites in Eastern Germany

- 1991 Transformation into a remediation company, sole shareholder Federal Republic of Germany

  Task by law: sustainable rehabilitation of large-scale radioactively contaminated sites

Rehabilitated area

Main remediation tasks

- Decomissioning/savekeeping and controlled flooding of underground mines
- Demolition and rehabilitation of processing plants and operating areas
- Water treatment
- Monitoring, environmental reporting, maintenance

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Remediation Tasks


Demolition shaft 388/390


Covering Tailings ponds Culmitzsch


WTP Königstein


Monitoring

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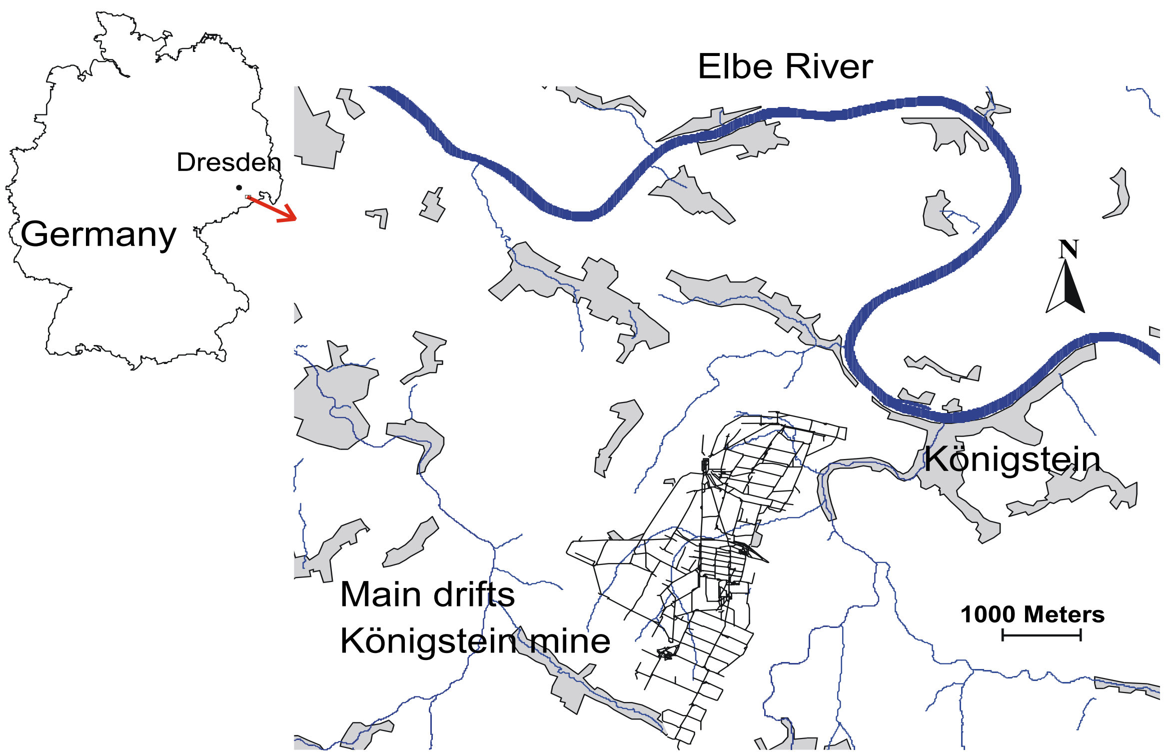
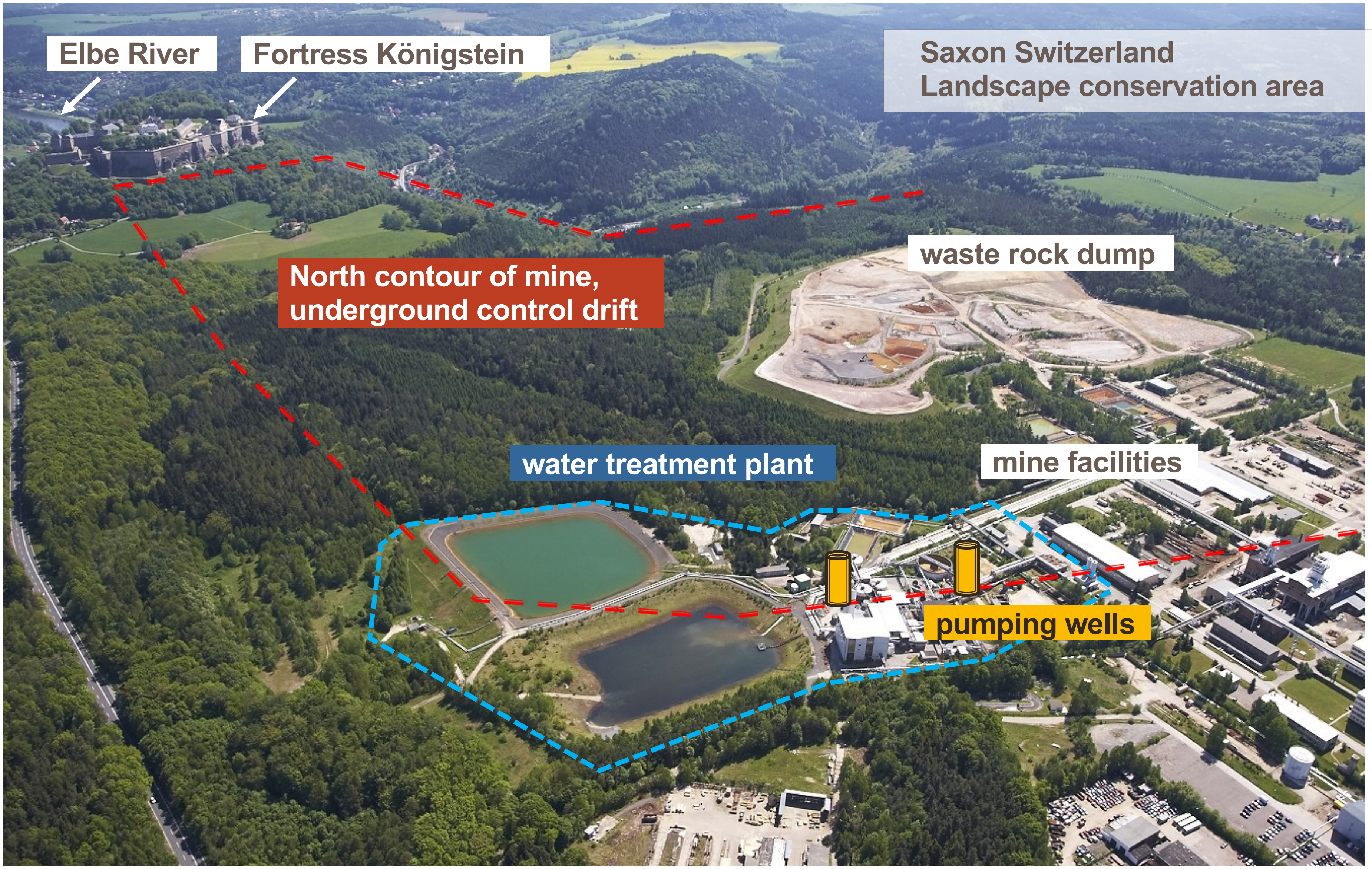
Wismut remediation area – Introduction Königstein site

Location of the Königstein mine

- Situated in an ecologically sensitive and densely populated area near the National Park Saxon Switzerland
- Shortest distance to Elbe River: approx. 600 m




Elbe River
Fortress Königstein
Saxon Switzerland
Landscape conservation area
waste rock dump
North contour of mine,
underground control drift
water treatment plant
mine facilities
pumping wells

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History of the Königstein underground uranium mine

- 1961 Start of exploration
- 1967 Start of exploitation (conventional mining)
- 1984 Change to a leaching technology (inside the mine)
- 1990 Completion of Exploitation

- 1991 First Remediation concept including flooding concept
- 1993 Start of flooding experiments → preparation flooding sec. I
- 2001 Start flooding section I (max. 140 m a.s.l.) after 10 years R&D
- 2012 Mine is closed after total backfill of shafts 388/390
- 2013 Completion flooding mine section I, 140 m a.s.l.
- 2017/18 Full scale Hydraulic test → preparation flooding section II
- 2020/21 Hydrochemical test

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Period of conventional mining 1967–1983
Room-and-pillar mining with bashing/partial filling

Extraction methods with one or more slices depending on ore thickness

bunker loader

Carriage drilling

Worsening of extraction conditions at the end of 1970´s

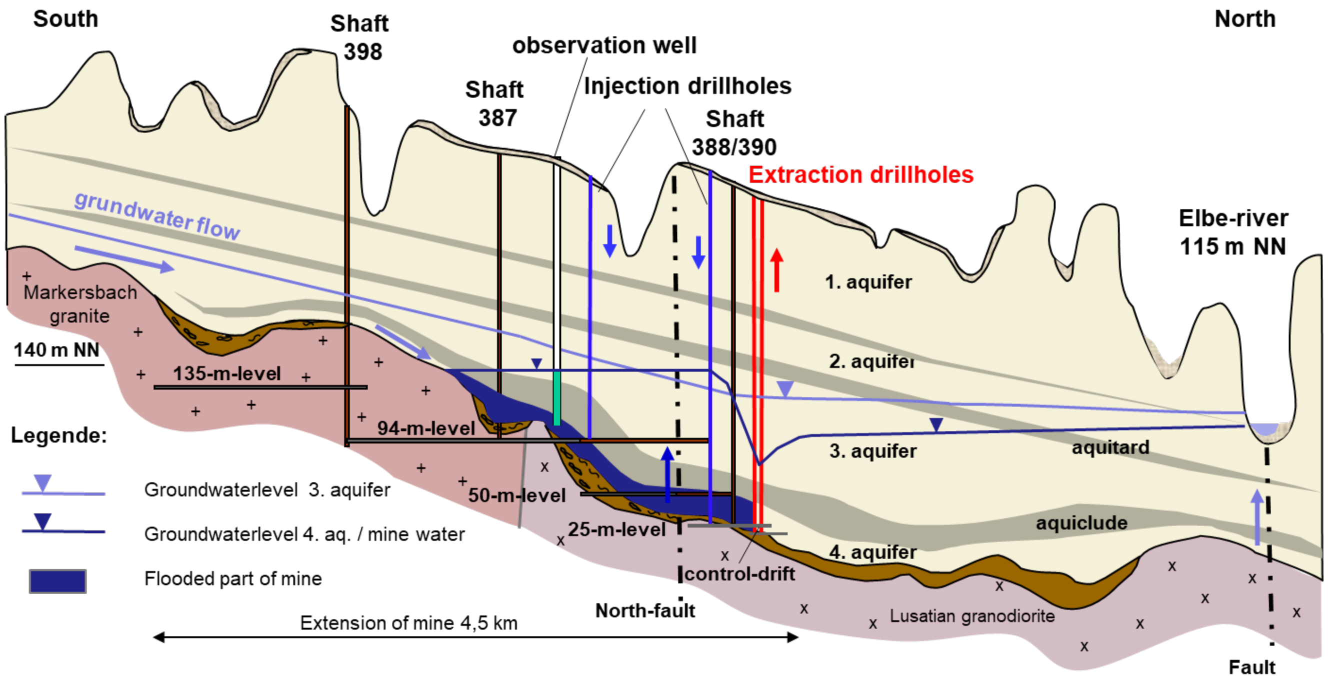
- Declining uranium concentration and ore thickness
- Extension of the extraction area and shifting to outer sections of the deposit
- Uranium production until 1983: app. 12,000 t

Changeover of the mining technology - Period of underground leaching

- First experiments for chemical exploitation 1969
- Since January 1984 exclusively chemical exploitation
  - **Underground in situ leaching** method using sulphuric acid (solution 2-3 g/l)
  - Performed in more than 100 sandstone blocks
  - Using drifts drillings and tubes for injection and drainage
  - during the leaching period altogether 130,000 t sulphuric acid were applied within the deposit
  - Unknown amount of sulphuric acid was produced by pyrite oxidation
  - app. 5,750 t uranium production by leaching operations

Geochemical status was substantially changed with a high pollutant level remaining within the deposit (sulphate, heavy metals and natural radio nuclides)

Hydrogeological conditions in multiaquifer system



- Uranium roll-front sandstone deposit in 4th aquifer
- 4 aquifers separated by clay- and siltstone aquicludes and aquitards
- 3rd aquifer main potable water reserve at Königstein area
- Interaction 3rd and 4th aquifer play the main role during flooding process

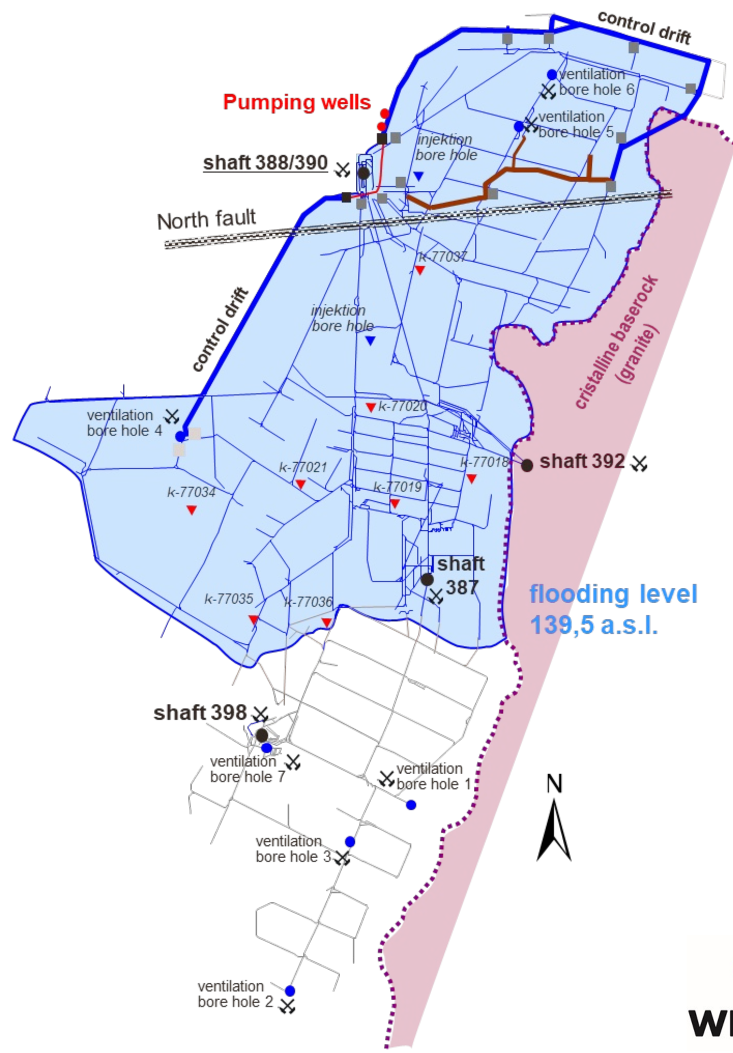
Remediation tasks and strategy

Particular conditions

- Extracting technology underground leaching by sulphuric acid: mine water with pH 2, up to 200 mg/l U, 150 mg/l Zn
- Aquifer conditions, preventing contamination of potable water reserve in 3rd aquifer

Implementation of conventional remediation concept not possible

- Flooding up to natural level unique sustainable possibility
- Development of the concept „Controlled flooding of the Königstein mine“ up to a level of 140 m a.s.l. (section I)
- Construction of a special underground system for drainage of polluted water
- Concept for stepwise final flooding up to natural level of 200 m a.s.l. (section II)



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Preparation for Flooding, mine section I

Precondition of mine flooding:

- Prevent any downstream to get water license,
  break-off after detection of any downstream into 3rd aquifer

↓ intensive system analysis for evidence, intervention plan

Research and Development: (~ 10 years)

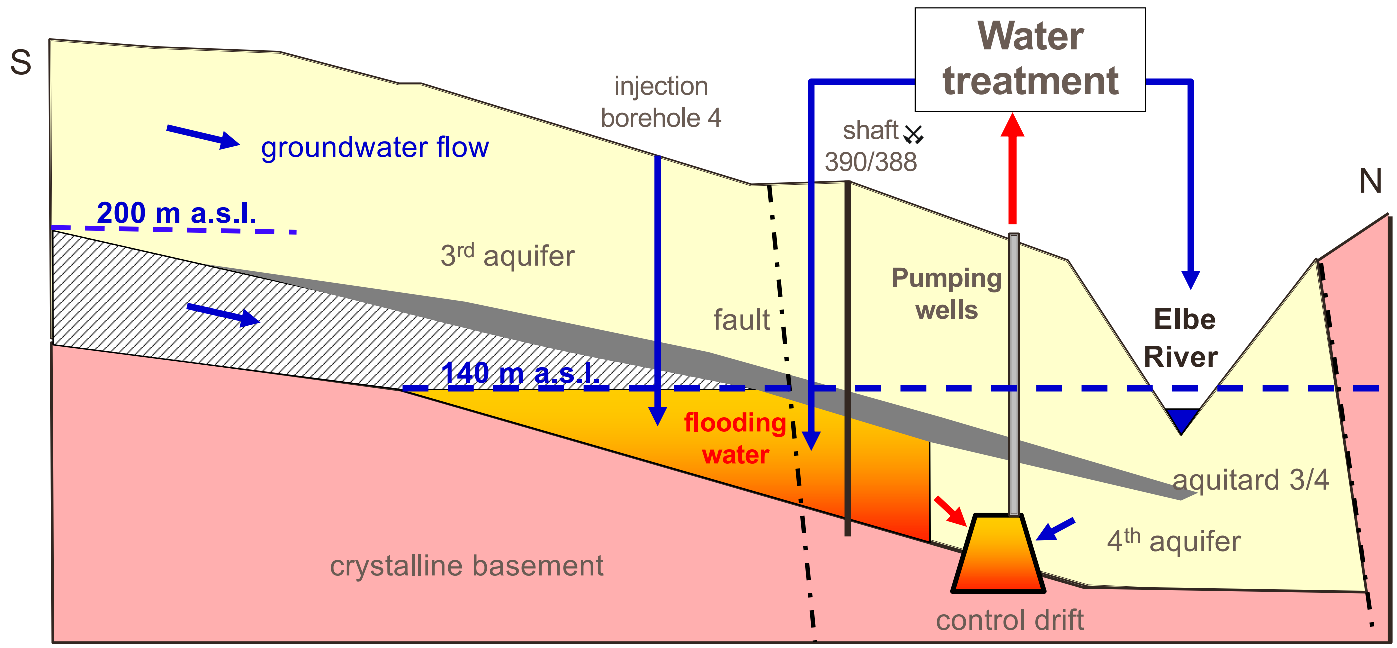
Scientific studies (~200) for system analysis and remediation concept

- Hydrogeological situation and development in the aquifer system
- Fill-up and connected downstream process of mine water
- Pollutant potential, pollutant dispersion and approaches for long term immobilization
- Optimization of water treatment plant, radioprotection aspects
- Monitoring, analysis and understanding of complex system

→ Flooding up to 140 m a.s.l. did not lead to downstream and contamination of 3rd aquifer

Flooding status of the Königstein mine

- After licensing 2001 - 2013: stepwise flooding up to 140 m a.s.l. with simultaneous water removal and injection (washing)
- Currently: stable water level (up to 139.5 m a.s.l.), washing (150 m³/h) →
- Increase pH value up to 3; wash out of 1,000 t U
- Water treatment



Lessons learned from flooding mine section I

- Controlled flooding of the Königstein leaching mine has been performed in a technological and environmentally safe procedure.
- The release of contaminants proceeded as expected: first flush (intensive release from open mine workings) followed by a slow supply from pore space of sandstone over the long term.
- Roughly 60 % of the mobile pollutants have been washed out.
- The primary remediation principle, an active washing out of pollutants, has been proved and demonstrated to the regulators.
- Forcing of natural attenuation, in particular sulphate reducing processes, is possible by increasing pH: injecting of alkaline solutions.

Mine water still contains soluble contaminants (heavy metals, U, Ra) and must be pumped and treated.

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Preparation for flooding mine section II

Precondition of mine flooding:

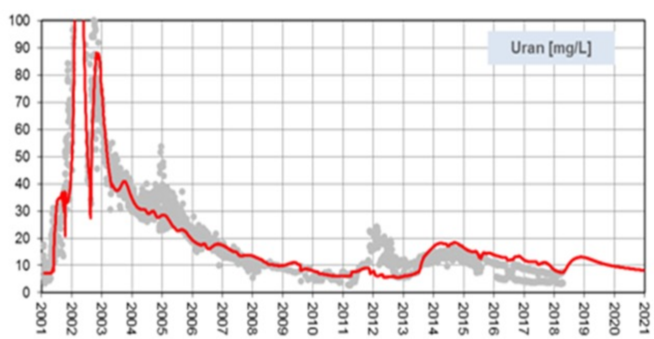
- Comprehensive analysis/evaluation of flooding mine section I
- 100 % prevention of downstream and hydrochemical impact not possible → expert discussion with licensing authorities

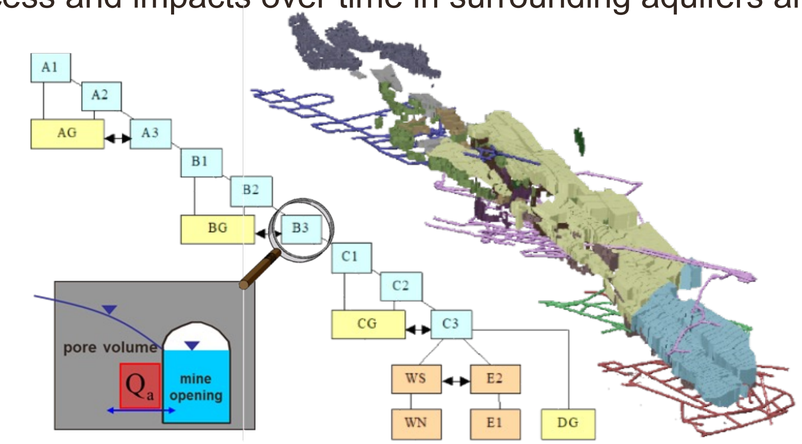
Enhance mitigation measures (R&D) licensing of limited testwise flooding

Research and Development: (~ 20 years)

Scientific studies (~300) for system analysis and remediation concept

- Laboratory investigations for neutralization and in-situ precipitation of contaminants
- Proceed Model development for flooding process and impacts over time in surrounding aquifers and the Elbe
- Execution of full scale field tests





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Field scale ARD mitigation measures

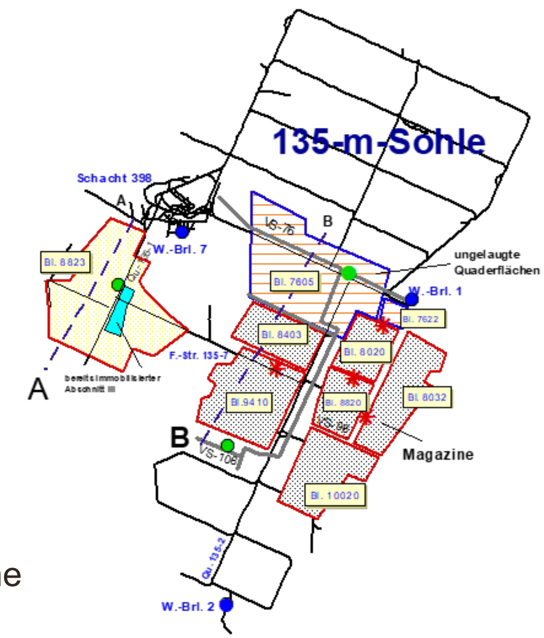
Immobilisation of leaching blocks

Objectives:

- Enduring fixation of contaminants in sandstone leaching blocks
- Reduction of hydraulic conductivity

Method: Controlled precipitation of barite in the pore volume of sandstones

- Application of sodium-silicate / bariumhydroxide solution at accessible blocks
- Process development since 1993
- Realization between 2001 – 2005



Results:

- conditioning of 1.6 Mill m³ sandstone with 325 t m³ immobilization solution
- 50% of the mobile contaminants have been fixed in the sandstone

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Field test with injection of alkaline solutions

Objectives:

- Reduction of acidity, induce reductive conditions to decrease contaminant concentration in mine water, investigation of solution transport in the mine, test of effectiveness of technical application

Method: Controlled injection of alkaline and reductive solutions into an existing injection borehole and in observation well into partly flooded mine

- Application of sodium-hydroxide / potassium-hydroxide / sodium-sulfide
- injection of 34 t KOH, 78 t NaOH, 7 t Na_2SO_3 with 100,000 m³ water
- Average pH value 12
- Carried out 08/2010 – 04/2011
- 3 partial tests with different injection and monitoring places in the mine
- Test the application under different flow conditions in the mine
- Intensified monitoring

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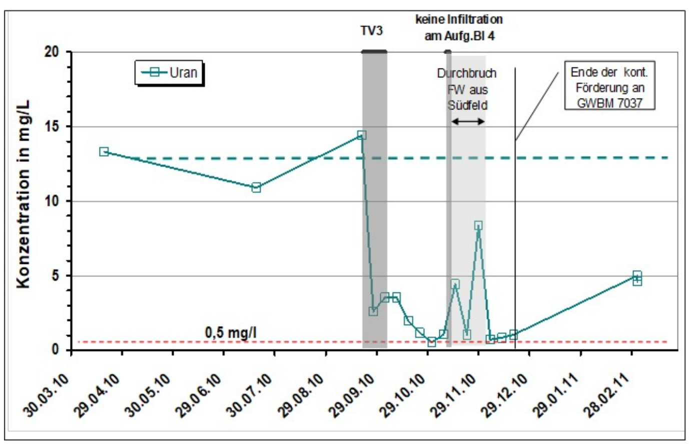
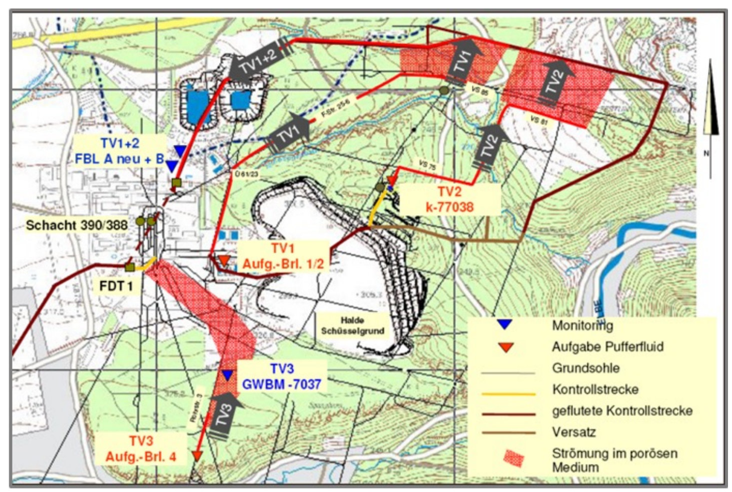
Field test with injection of alkaline solutions

Results:

- Neutralization and decreasing of redox potential of mine and interstitial water led to precipitation and fixation of contaminants with iron hydroxides
- Concentrations of uranium and heavy metals decreased down to 10 % of initial mine water concentration
- Flow paths in the mine were confirmed
- Technical feasibility in full scale was demonstrated
- Field test led to further development of supporting actions for mine flooding and advanced acceptance of flooding concept for section II





Hydraulic Test 1

Objectives:

- Test of system behavior, interaction of mine water body with the 3rd aquifer above 140 m a.s.l.
- Strongly limited downstream of mine water into the 3rd aquifer in approved observation and intervention area: for calibration of models, testing functionality of observation system, testing of retrieveability of hydrochemical groundwater pollution

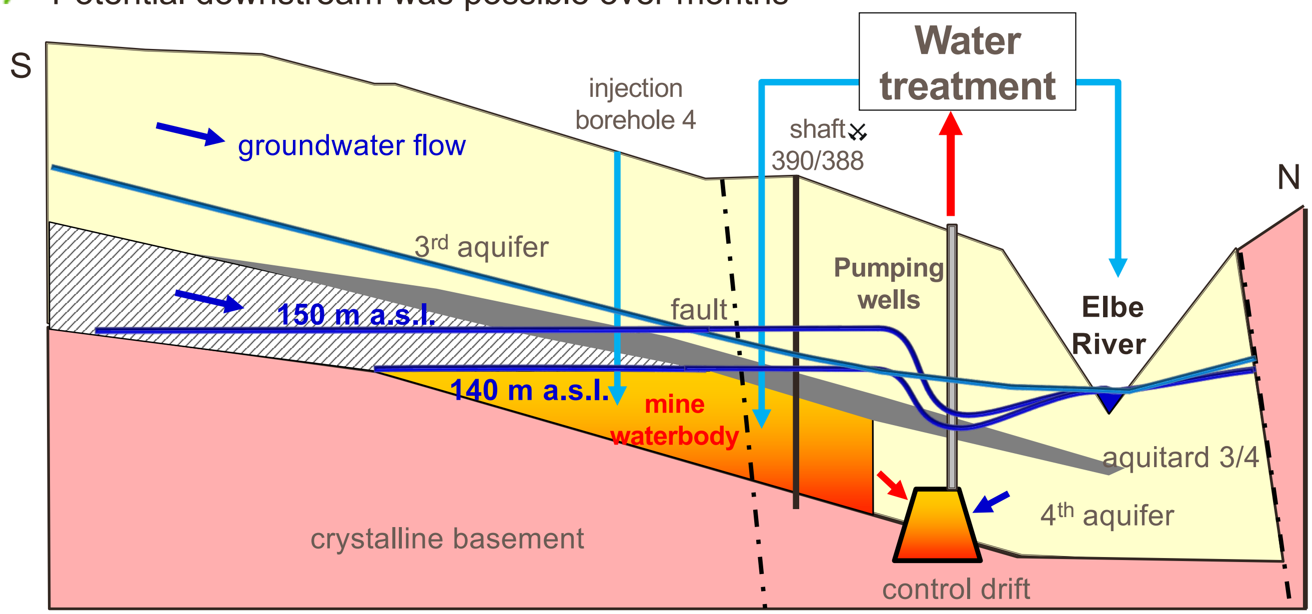
Method: Controlled flooding of the mine up to 150 m a.s.l. and immediate drawdown to 140 m a.s.l. (impounding of 700,000 m^3)

- Flooding phase: higher injection rates via injection borehole 4 and 1
- Drawdown phase: without technical injection
- Longterm pumping test downstream hydraulic gaps
- Enhanced and intensified groundwater monitoring
- Intervention plan to interrupt test after improper contamination of 3rd aquifer
- Carried out after approval from July 2017 to June 2018

Hydraulic Test 1

Results:

- Hydraulic behavior: increase of mine water level of 10 m led to an increase of groundwater level of only 1 m
- Observation wells in northern part of mine showed lower water levels in 3rd aquifer compared to the water level in the mine
- Potential downstream was possible over months



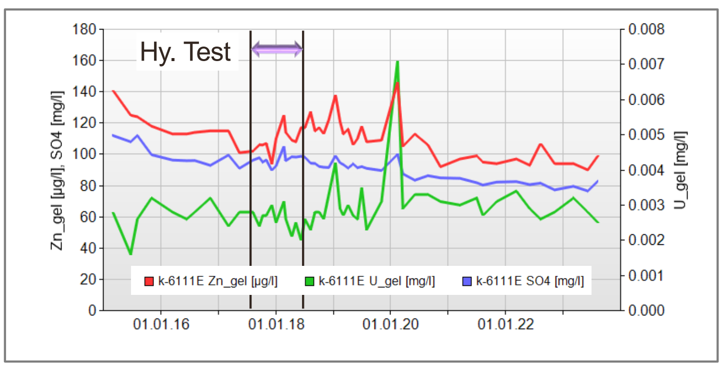
Hydraulic Test 1

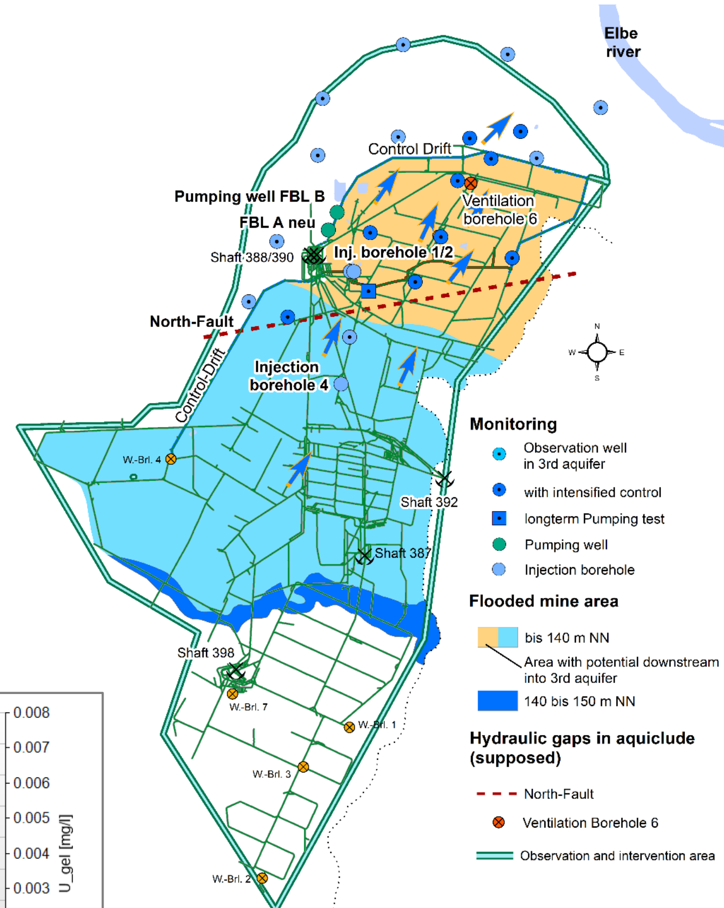
Results:

- No detectable downstream measured
- Assumptions in hydrochemical models too conservative adjustment of calibration
- System of observation wells has good functionality
- Retrieveability of groundwater pollution is limited and connected with large effort

Step in the right direction:

- ongoing negotiations with licensing authorities
- approval of further field scale tests





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Hydrochemical Test

Objectives:

- Transfer of the results from laboratory scale tests for neutralizing and initiation of reductive processes into a full field scale Test in the mine
- Evidence of enhancing microbial activity to reduce contaminant concentration in the mine
- Quantification of long-term reduction of contaminant concentration due to the injection of reactive solutions

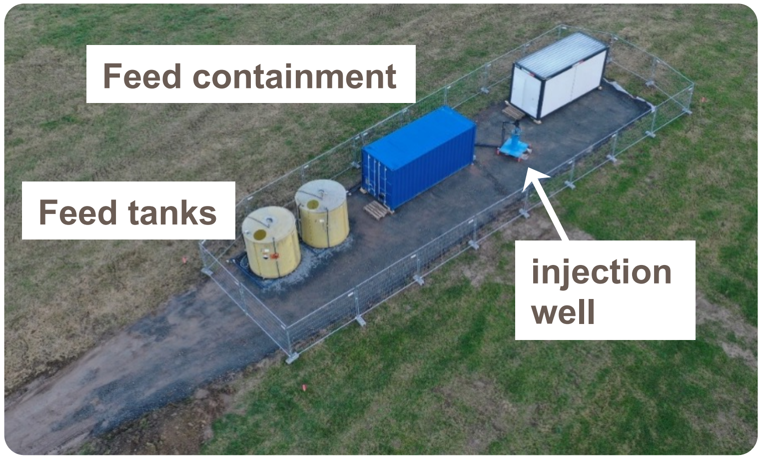
Method: Injection of alkaline and reductive solution in a single observation well with pore space conditions

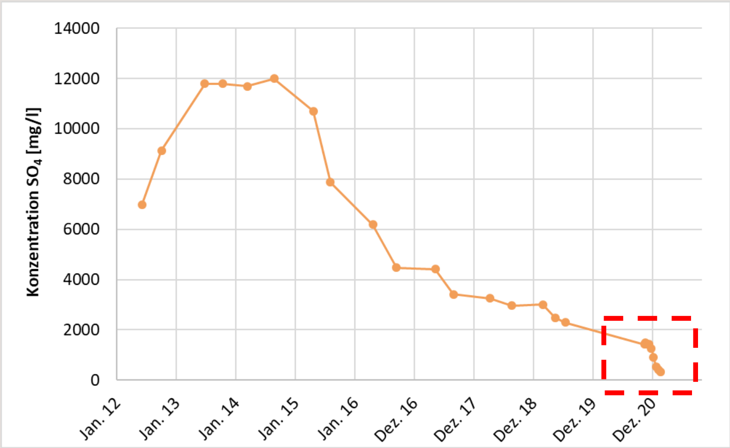
- Application of NaOH, KOH (tracer) and butanol
- Cyclic injection of reactive solution over 7 months
- Enhanced and intensified groundwater monitoring over 9 months
- Analyzing during pumping phase
- Carried out after approval from Nov 2020 to Aug 2021

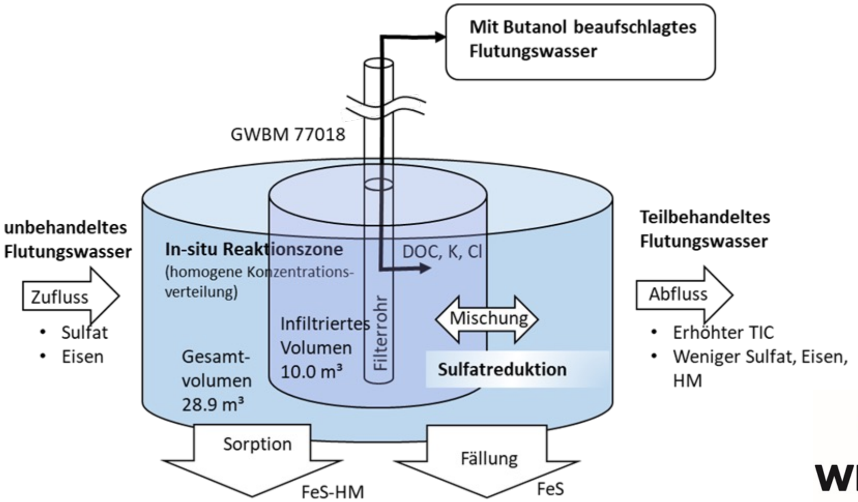
Hydrochemical Test

Results

- Tracer test showed the low downstream velocity and the controlled reaction space
- No clogging of pore spaces with precipitates
- Technical application in full mine scale possible
- Increasing rates of sulphate reduction
- Increasing sulfide concentrations







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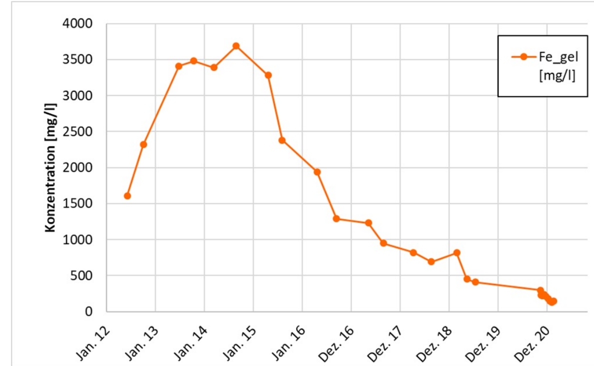
Hydrochemical Test

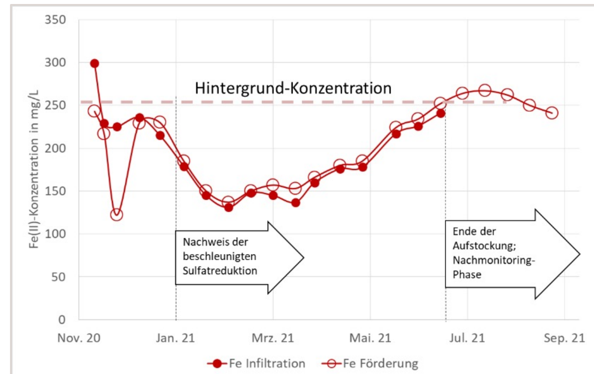
Results

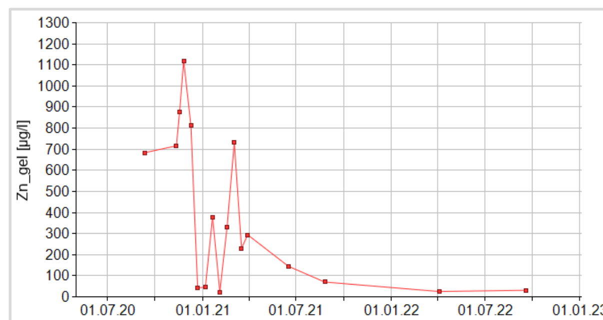
- Microbial oxidation: buthanol → carboxylic acids
- Increasing precipitation of Fe-II but delivery from outside the reaction cell
- Coprecipitation of heavy metals, e.g. zinc
- Combined injection of alkalinity and organic carbon source lead to enhanced microbial supported reduction processes
- Application suited to reduce acidity and contaminant concentration in full mine scale

Next step in the right direction:

- ongoing negotiations with licensing authorities for approval of testwise flooding in section II







Hydraulic Test 2 (upcoming)

Objectives:

- Test of system behavior, interaction of mine water body with the 3rd aquifer above 140 m a.s.l.
- Measureable but limited downstream of mine water into the 3rd aquifer in approved observation and intervention area: for calibration of models, testing of the proactive intervention plan for prevention of improper contaminations

Method: Controlled flooding of the mine up to 150 m a.s.l. with injection of reactive solutions

- 1 year flooding phase: higher injection and pumping rates via injection and pumping wells (→ secure hydraulic depression area)
- Injection of NaOH, KOH and butanol in the first 3 years
- Intervention plan to interrupt test after improper contamination of 3rd aquifer
- Approval at the end of 2022
- Planned to carry out from March 2024 in a period of 10 years

Conclusions and Perspective

- Königstein mine was partly flooded up to 140 m a.s.l. without mine water impact to the groundwater in 3rd and 4th aquifer
- Final flooding up to 200 m a.s.l. of the mine (entry with hydraulic Test 2):
  - 2024 to ~ 2040 stepwise realization with 10 m every 3 years
  - connected with neutralization of mine water and in situ precipitation of contaminants with approximation to pre-mining hydrochemical conditions
- 2024 to 2026 dismantling of uranium sorption plant, afterwards surface remediation
- After 2040 stop pumping and finally dismantling of water treatment plant → mining site will be completely remediated
- Groundwater monitoring will be necessary years or decades furthermore

… It's a long and expensive way to remediate a leaching mine in Germany…

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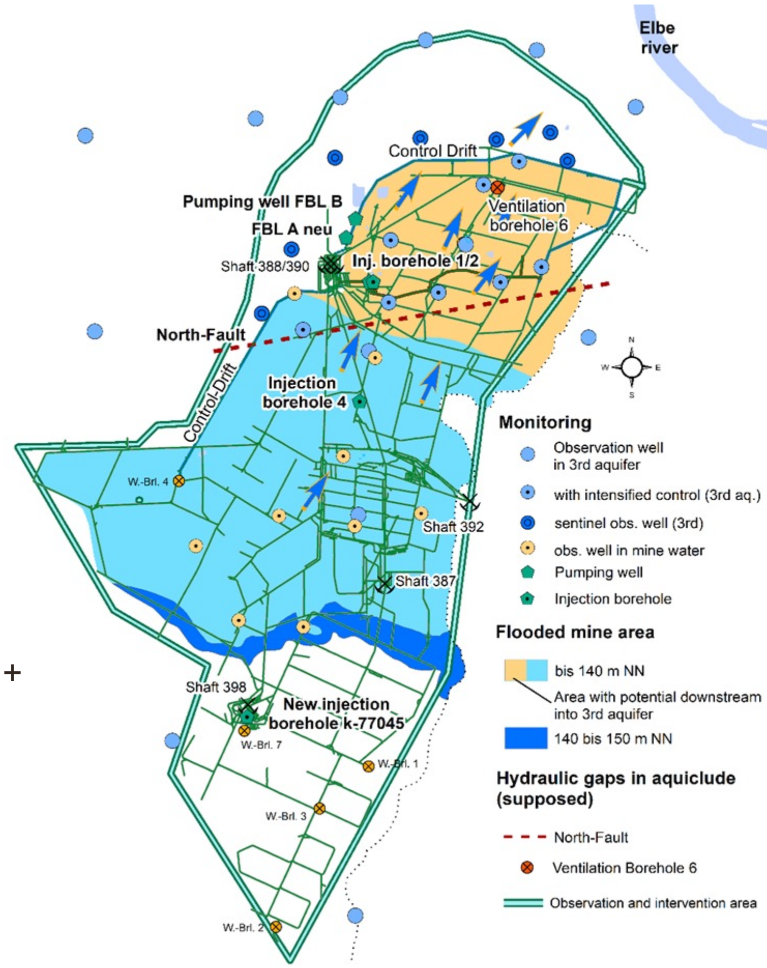
Thank you very much for your attention!

Hydraulic Test 2 (upcoming)

Proactive stepwise Intervention plan:

- Ensure compliance with contamination limits in a downstream intervention area
  → determined on basis of background values (100 µg/l uranium)
- Identify contaminations with an enhanced groundwater monitoring
- After identification above the limits at sentinel obs. wells: pumping at affected observation wells + intensified limit control
- Ongoing trend for expansion over the limits
  → break-off hydraulic test with drawdown mine water level below 140 m a.s.l.



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Hydraulic Test 2 (upcoming)

Preparation for Injection of reactive solutions:

- Plan: injection of 300 t NaOH, 100 t KOH, 2 t butanol each year in the first 3 years
- Increasing of pH value and support microbial sulphate reduction
- Planning, construction and building up of a mobile injection plant
- Drilling and supporting of a new injection borehole in the south of the mine
- Ongoing extensive search for new collars to built up further injection boreholes for improvement of the effectiveness of injection