Steam-Air-Injection in fractured bedrock: Experience and lessons learned from a CHC contaminated site

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Introduction: site situation and remediation method

On the site of a former incineration plant for liquid organic waste contaminants (CHC, BTEX) percolated in the underlaying aquifer systems. During the demolition of the plant and the excavation of the top soil about 1,600 kg of CHC were removed. The remaining source zone in the deeper layers covers an area of approx. 2,800 m² and a depth of 37 m in the affected fractured sandstone aquifers. The corresponding plume extended over several hectares. The concentration of CHC in the groundwater ranged from 1 mg/l in the saturated zone to up to 40 mg/l in the surface water drainage system (6 m bgs.). The content of CHC in the soil vapour was up to 4 g CHC per m³ in the source zone. The upper zone of the sandstone aquifer (15 m bgs.) and the unsaturated zone contain the majority of contaminant mass.

In 2009 VEGAS accomplished a pilot trial of steam-air injection on demand of the problem owner, the city of Villingen-Schwenningen, Germany. The heating period by steam-air injection lasted for 19 weeks. The test field extended to 2,000 m³ of fractured rock including the upper aquifer. Contaminants that had penetrated into the sandstone matrix were thermally desorbed during the conductive heating of the bedrock. More than 91 % of the total extracted mass (560 kg CHC) was removed from the groundwater fluctuation zone and the unsaturated zone via the soil vapour extraction system, less than 6% thereof via the groundwater containment (34 kg of CHC). The CHC values in the soil vapour and the groundwater were decreased by 95% and 85%, respectively.

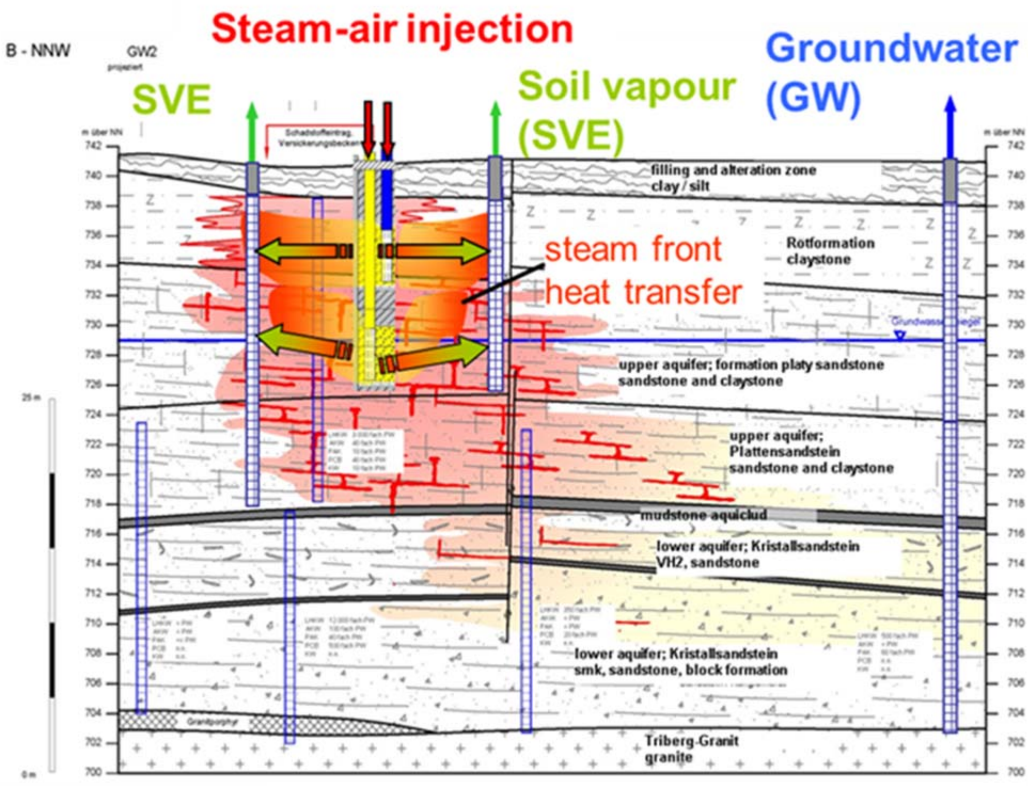

Figure 1: Soil profile and set up of injection and extraction wells based on the results of the pilot

Remediation concept, design and implementation

Based on the results of the pilot trial, the steam-air enhanced remediation of the groundwater fluctuation zone and of the unsaturated zone for the entire site was designed. The site to be treated extends to about 15 m depth, 40 m width and 70 m length (43,000 m³ in volume), see fig. 2. In total there are 32 two-level injection wells, 37 soil vapour extraction wells and 3 groundwater wells downstream of the contaminated area. 89 temperature measurement lances used to monitor the heat propagation at 20 different vertical profiles simultaneously.

The initial design was to treat the site stepwise in sections of approximately 4,000 m³ of fractured sandstone and claystone each following the groundwater flow direction from north to south. Each of the total 9 sections is equipped with 4 – 5 dual injection wells surrounded by 10 - 12 SVE wells. The grid distance between the injection wells is 7 m, the distance between SVE is 10 m.

The heating power ranges between 300 and 450 kW when simultaneously operating 8 to 10 injection wells with injection pressures of 1.4 (top level) and 2.6 bar (sandstone). The soil vapour extraction rate of the corresponding 10 SVE wells operating at 150 mbar vacuum exceeds 600 m³/h.

The thermally enhanced remediation was designed to last 30 to 33 months (until April 2015). The costs were estimated to be 2.6 million EUR to treat 43,000 m³ of sandstone during four years of operation.

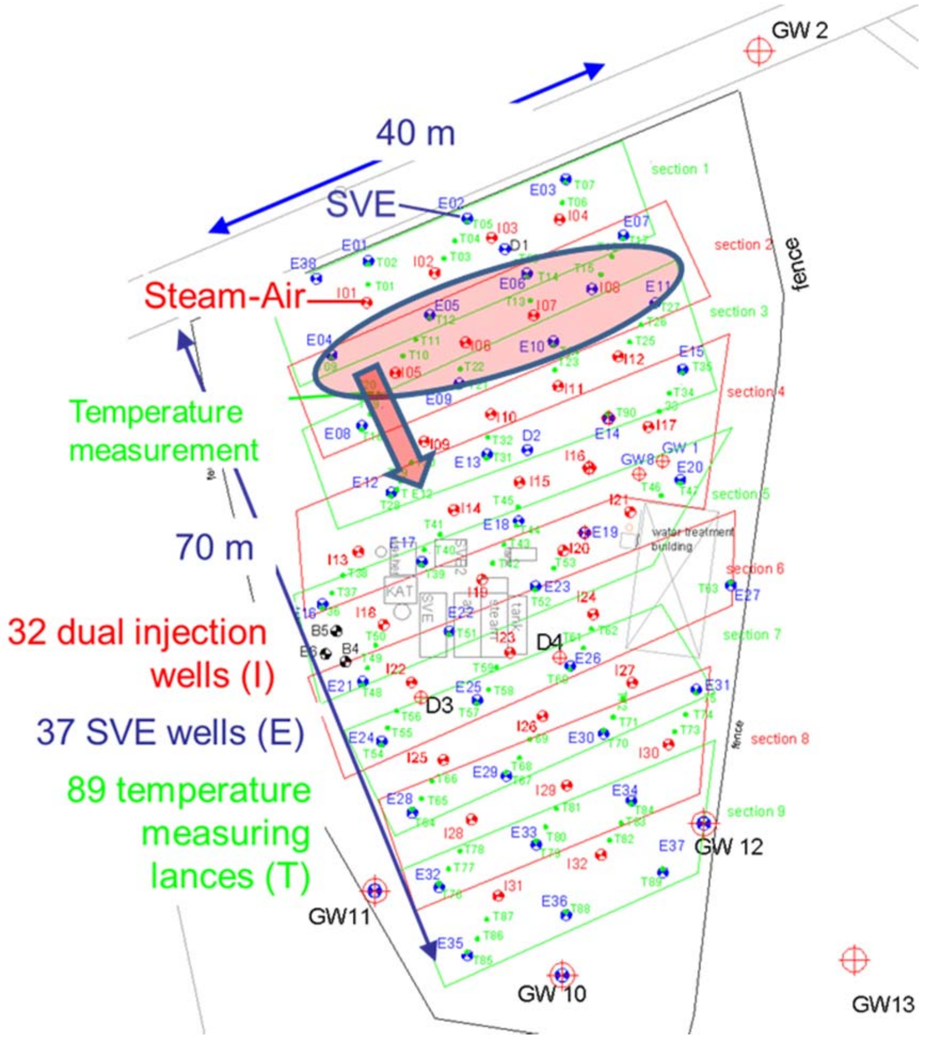

Figure 2: Map of the field site with the required installations for steam-air Injection

The site is hydraulically contained downgradient of the treated area by two wells (GW11, GW12) operating in the upper aquifer (sos) and one well (GW10) in the lower crystalline sandstone aquifer (smk). The total discharge of this groundwater containment is 12 – 14 m³/h to capture the overall downgradient contaminant emission. To monitor the emission from the site a second line of observation wells (GW13 – GW16) is located 20 m downstream of the site. These wells were also be used for hydraulic containment.

Operation of the remediation and unexpected surprises

The steam-air driven remediation started in July 2012 and was originally planned to end in April 2015. The reality though was quite different. The needed remediation time had to be increased due to different reasons, so currently the steam injection phase will last until July or August 2016. Up to now the total CHC mass removal already sums up to more than 5,000 kg.

During the remediation the heating strategy and the soil vapour extraction system had to be adopted according to the remediation progress and to the real circumstances since the desorption process of the CHC from the sandstone bedrock is slower than determined during the pilot study. The time demand will be increased by 35%, the energy consumption by 25%. Since the heat and steam propagation is wider than expected the steam-air injection was not the limiting factor but the soil vapour extraction system (SVE). This has to be extended several times to ensure pneumatic control and to extract a maximum of contaminants. The energy is effectively stored in the bedrock. During desorption phase the average temperature exceeds 88°C in heated sandstone.

Moreover, compared to the pilot, unexpected transport and displacement of evaporated contaminants in the fractures is observed. The monthly depths-specific monitoring of the SVE-wells indicates an almost complete removal of the contaminants from the upper sandstone and the claystone layers between 3 – 8 m bgs. The CHC contents are less than 10 mg/m³. In some parts of the lower platy sandstone CHC contents of 100 – 300 mg/m³ were detected after thermal treatment of the section. This indicates a mass removal of more than 90%.

The duration of the cooling time is expected to last for 6 - 8 months while contaminants might still evaporate from the sandstone.

Table 1: Comparison of design and effective remediation strategy

Design of remediation process (2010)	Applied remediation process (2013 – 2016)
• 9 sections	• 9 sections → transient steaming of 2 sections simultaneously
• stepwise downgradient duration 3 months each section	• stepwise downgradient duration 7 months each section
• 2 injection levels, 5 wells	• 2 injection levels, 5 – 8 wells → 2 section
• 450 … 300 kW total power	• 500 …350 kW total power
• Heating strategy: 6 weeks heating and steam propagation in both layers + 8 weeks desorption time	• Heating strategy: 5 weeks heating and steam propagation of claystone (sot), 200 kW + 11 – 13 weeks desorption time of claystone incl. heat propagation in sandstone (sos), 300 kW + 9 weeks desorption time (sos), 150 kW
→ one week cooling SVE time for each section	→ Six to eight months final cooling SVE time

Surprise (1) heat propagation: consequence and measures

The steam propagation in each section was accomplished and monitored during the first 6 – 8 weeks after starting the injection by a continuously increase of the temperature. The steam front arrived at the extraction wells four weeks after start-up. The heating phase needed 8 – 10 weeks (see Figure 3, section 1 and section 2) to reach constant temperatures above the desired azeotropic temperature of 88°C in the saturated zone. During the treatment of section 1 and 2 the average temperature in the unsaturated zone above 11 m bgs was below 65°C. Hence, the azeotropic temperature was not met. Therefore the evaporation of the contaminants was slower as expected and planned; as indicated by the (slow) increase of mass removal during the treatment of section 2 (see Figure 4).

Due to a change of the treatment concept the target values in both zones of section 2&3 could be reached during the treatment. In consequence of the water displacement by steam and the continuous operation of the groundwater capturing system the water table fell below 14 m in the treatment zones whereas the pressure head was higher. Therefore the target temperature was defined to be between 80 to 82°C for both zones. In the beginning of 2014 the treatment of section 4 started. The average temperature between 13 – 3 m bgs. was maintained to be above the target temperature.

The average temperatures of the various distinct levels in the subsurface, sot and sos indicate lower temperatures due to the lower temperatures in the outer extraction wells extracting a mixture of steam and colder ambient air.

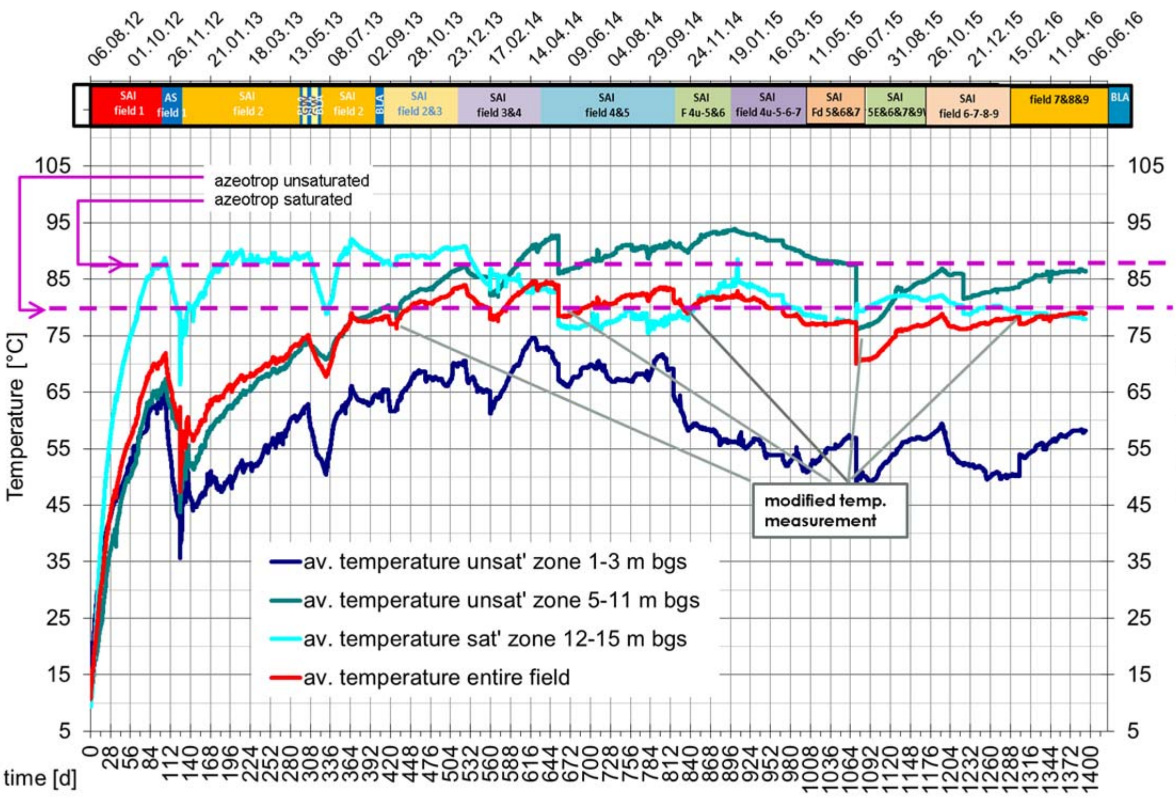

Figure 3: Temperature development during remediation process

Resulting contaminant removal

The remediation process starts with the steam propagation in the fractures and with the direct heating of the highly contaminated surface of the sandstone close to the fractures and its fast thermal desorption. The first steam breakthrough at the extraction wells is typically accompanied by a high mass removal rate of contaminants (Figure 4). The effect is mainly and mostly visible after 1 - 2 weeks of steam-air injection in a new treatment section. During the first 8 – 10 weeks the bedrock is heated up while the contaminant mass removal increases. Passing peak of contaminant removal the desorption phase continues. Once the contaminant extraction goes below 2 kg/d of CHC removal, meaning 100 – 150 mg CHC per m^3 of soil vapour the next treatment section is added to the steamed area.

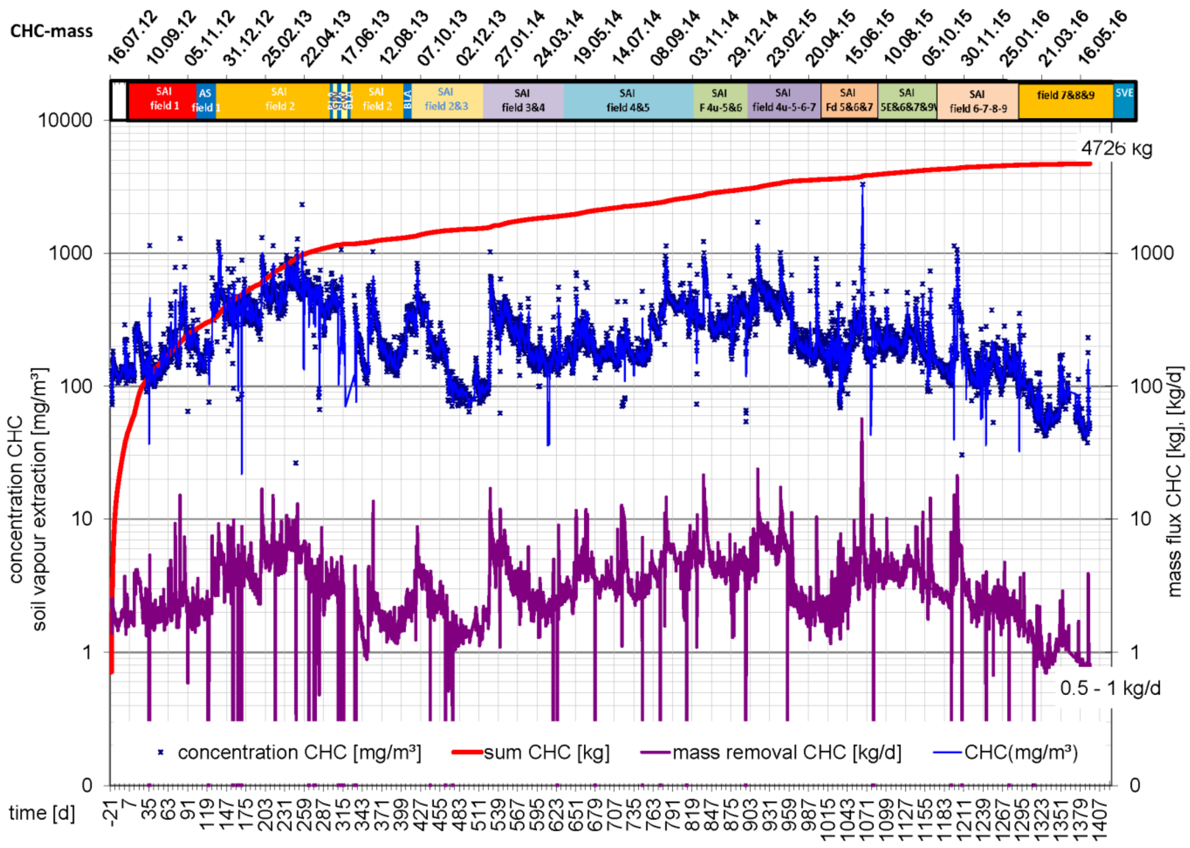

Figure 4: CHC removal rate, total extracted mass and concentration in soil vapour extraction

Until the end of May 2016 more than 4,900 kg of CHC were removed on site. Approximately 4,700 kg CHC were removed by the SVE and 200 kg CHC by the groundwater containment. Including the pilot trial in 2009, more than 5,400 kg CHC were removed by the soil vapour extraction during the thermally enhanced remediation.

Surprise (2): contaminant distribution in the soil vapour and resulting measures

The remediation process is monitored by a monthly analysis of the soil vapour from all SVE-wells on the site. The major criterion to conclude the treatment of a single section is to achieve a threshold level of less than 20 mg CHC per m³ of soil vapour. The temporal development of the spatial CHC distribution indicates the successful remediation (from red to blue, Figure 5) of the sections from north to south. Green and blue marked areas indicate the target values of the contaminant concentration level after the treatment. The red coloured areas indicate the initial contaminant concentration of more than 800 mg/m³.

Starting in 2014 the development of the decreasing concentrations was “as expected” or “planned” (March 2014 to Sept. 2014, Fig 5). However, in the beginning of 2015 (see March 2015), during the thermal treatment of the sections 5 – 7, the CHC content in the soil vapour of the lower sandstone layers (sos) increased by one or two orders of magnitude. This effect was not observed in the upper sand- and claystone layers (sot). The different concentration levels in sot and sos indicate a migration of contaminants from the lower part of the sandstone below 14 m bgs or a rebound from the compact bedrock. A couple of wells in section 3 still have had temperatures above 70°C and elevated values of CHC were observed. In section 2 the temperatures were ranging between 40 – 50°C. A slight overpressure of 20 – 50 mbar was found at some of the former injection wells in section 2 and 3. Therefore, ongoing evaporation processes and a steam flow enhanced mobilisation of contaminants from section 6 and 7 may cause the increase, too.

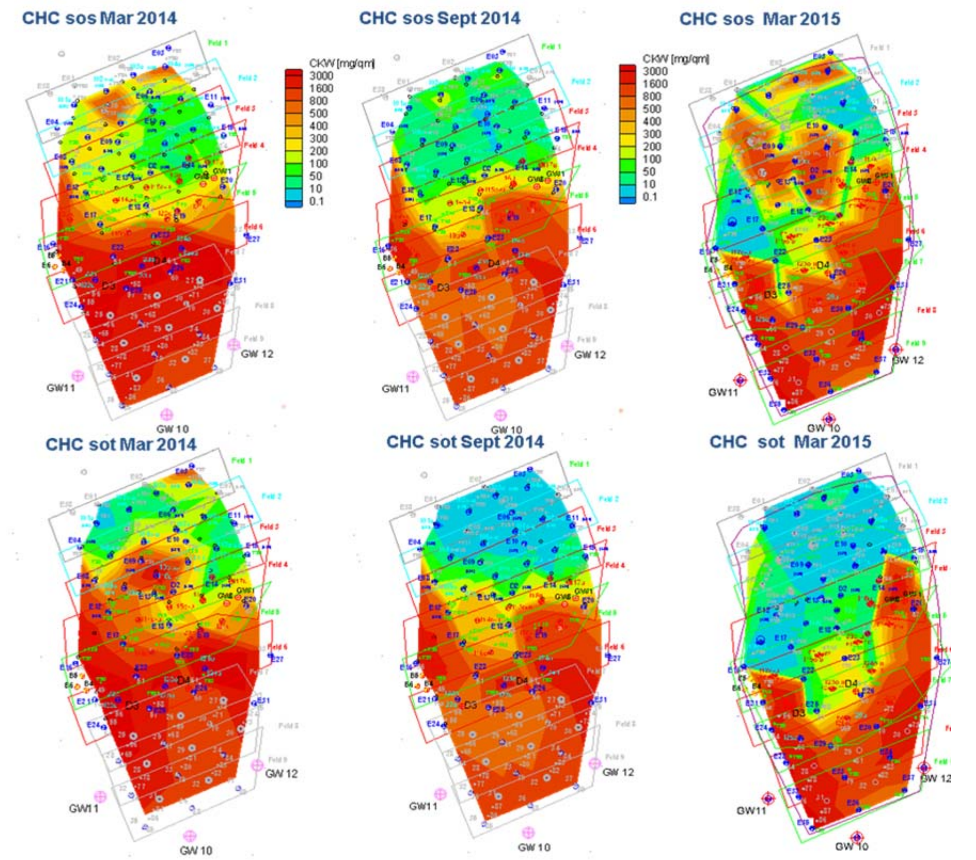

Figure 5: CHC distribution in the soil vapour between March 2014 and March 2015 for the lower sandstone layers (sos) and the upper sand- and claystone layers (sot)

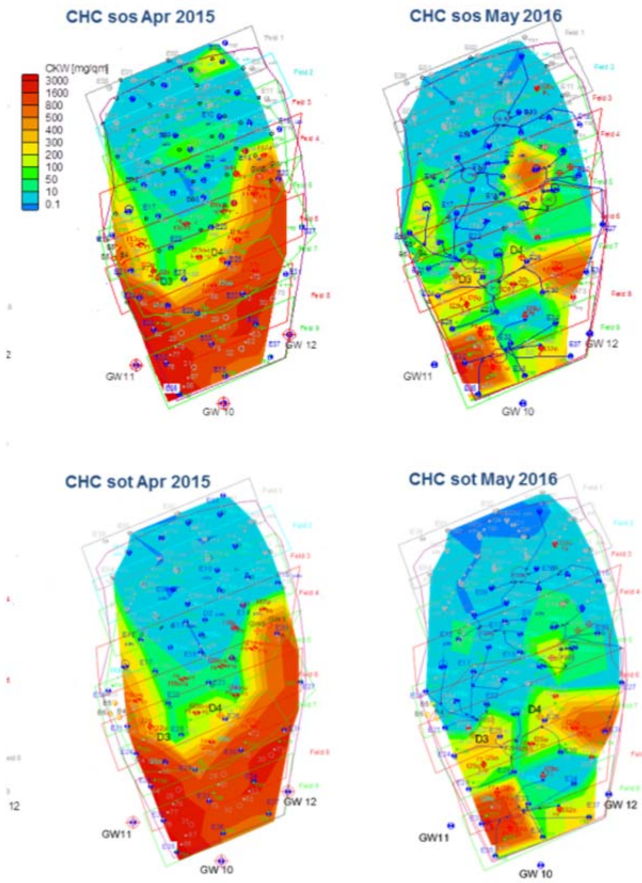

Figure 6: CHC distribution in the soil vapour between April 2015 and May 2016 for the lower sandstone layers (sos) and the upper sand- and claystone layers (sot)

An analysis and investigations of these rebound and migration effects during June 2015 resulted in a measure to create a negative pressure barrier between section 3 and 2 by turning off the steam injection for one week and monitoring and analysing the resulting CHC distribution. To avoid further contaminant mobilisation and to capture CHC from ongoing desorption processes, the SVE system was extended to operate 40 SVE wells. To enhance the desorption in the southern part, the steam-air injection in section 6-7-8-9 was increased by operating in total 20 injection wells.

Originally it was assumed, that the capacity of the steam-air injection (steam generator) will be the limiting factor for the remediation but due to the high number of extraction wells and the needed extraction rates and underpressure the soil vapour extraction system (SVE) was the limitation.

All these measures lead at least on the one hand to the promising CHC distribution shown in Fig. 6 (May 2016), but on the other hand it takes more time as originally expected. It was planned to shut off the steam-air injection in June 2016 it is now tentatively planned for July or August 2016.

Lessons learned

Thermal remediation using steam-air injection in fractured sandstone contaminated with chlorinated hydrocarbons is challenging. Although a detailed site investigation was done and a pilot remediation was successfully completed as basic for the design of the full remediation, during the execution various "surprises" came up which required flexible and partly quick measures to reach the remediation goal at the end. In consequence this project leads to several, valuable lessons learned and new experiences for the future application. Some points can be summarized:

- Flux and control spreading of evaporated contaminants in fractures is difficult and sometimes surprising
- Intensive online monitoring and prompt data analysis is required
- Adjustment and optimization of the remediation based on the monitoring data has to be made
- Heat transport and contaminant removal differs from the pilot trial, this requires additional measures and resources
- CHC removal by SVE is dominant: currently more than 5,000 kg CHC and only about 200 kg CHC by groundwater containment were removed
- Remediation procedure requires several times a flexible and quick adaption of the SVE system
- Additional time (money) is required: the remediation lasted 48 months instead of the originally planned 33 months.

Remediation of fractured bedrock by steam-air injection can be very successful but it requires an effective control, flexibility of the parties involved (consultant, remediation company, site owner, regulator) and financial resources.

Summary and outlook

On the site of a former incineration plant for liquid organic waste (CHC, BTEX) in Villingen-Schwenningen, Germany, a long lasting contaminant leakage causes a plume covering several hectares. The source zone extends over 2,800 m². The affected fractured sandstone aquifers are contaminated down to 37 m bgs. The upper platy sandstone comprising the groundwater fluctuation zone and the unsaturated zone contains the majority of the contaminant mass.

The application of a thermally enhanced remediation using steam-air injection was a new approach to remove chlorinated hydrocarbons from a fractured sandstone aquifer. A pilot application was conducted in 2009 to determine the effectiveness of the technology prior to designing the full scale thermally enhanced remediation scheme. The steam and heat propagation extended to 5 m in radius from the injection well. During the three months of operation approximately 560 kg of CHC were removed from about 2,900 m³ of fractured sandstone. A mass removal of more than 90% was indicated from the development of contaminant concentration in the soil vapour.

After a phase of planning and a request for tenders and commissioning in summer 2012 the full scale remediation started to treat approximately 43,000 m³ of sandstone and claystone. The site is divided into nine treatment sections. The duration of the steam-air injection phase (steam injection power of 400 kW) was calculated to last 33 months. A total of 32 two-level injection wells and 37 soil vapour extraction wells (SVE) were installed on site. The total costs of the four years running remediation will be 4 million EUR incl. tax.

During the remediation of the northern sections the concept of a compartment-wise treatment of the bedrock had to be adapted. Both, the effective heating time and the duration of the desorption phase were significantly longer than indicated during the pilot trial. The time demand was increased by 35%, the energy consumption by 25%. The heat propagation of up to 10 m in radius allowed the simultaneous treatment of two sections at one time. The steam and heat flux was less than 500 kW. This resulted in an effective doubling of the treatment time of a single section to more than 7 months duration which provided the required desorption time. In addition the SVE was revised and extended by 50% to cover 4 – 5 treatment sections simultaneously. Instead of the initially intended operation of 10 SVE wells and 4 – 5 two-level injection wells there are currently 40 SVE wells and 10 two-level steam injection wells under operation.

Until the end of May 2016 approximately 4,900 kg of CHC were removed from the site after the treatment of approximately 60 – 70% of the cubature. 4,700 kg of CHC were removed by SVE and 200 kg CHC by the groundwater containment. Including the mass removal during the pilot study, so far more than 5,400 kg of CHC were removed by the soil vapour extraction during the thermally enhanced remediation.

Despite the described difficulties/challenges, the effectiveness and applicability of the technology to remediate a CHC contaminated fractured sandstone and claystone was proven. Due to the irregular fractured system the duration of the desorption of the contaminants was prolonged by about 35% - 40 %. The remediation procedure was to be adopted, affecting both, cost and time. It is planned to finish the steam-air injection in July or August 2016 after 48 (49) months of operation.

Parties involved, responsibilities and acknowledgement

The environmental agency of Baden-Württemberg (LUBW), the regional council (RP Freiburg) and the community of Villingen-Schwenningen support the application of a thermally enhanced remediation of the site by steam-air injection. The pilot project was carried out with financial support of the Helmholtz Centre for Environmental Research, UFZ, Leipzig, the community of Villingen-Schwenningen and the regional council and the State of Baden-Württemberg. The local consultant GEOsens assisted the pilot study and is the leading consultant for the remedy, the scientific supervision for the pilot and the remedy is the responsibility of VEGAS. The remediation company is Bauer Umwelt GmbH.

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Short biography

Dr.-Ing. Hans-Peter Koschitzky
Technical Director, VEGAS, Research Facility for Subsurface Remediation, University of Stuttgart.

Civil engineer (graduated 1980, Dr.-Ing. 1987 in Hydraulics). From 1989 responsible for the planning and realisation of VEGAS, since 1995 technical director and since 2002 also executive director of the Institute for Modelling Hydraulic and Environmental Systems at the University of Stuttgart. Since 1995 directing numerous research projects in the area of in-situ remediation and supervising a number of successful field studies for remediation of organic contaminants. He was leader of a large WP (Simultaneous remediation of saturated and unsaturated zone) in the FP5-EU Project PURE (Protection of groundwater resources at industrially contaminated sites) and is leading some nationally funded R&D projects.

Core research competences and interest

- Thermal in situ remediation technologies (porous unsaturated/saturated zone, fracture rock)
- surfactants, alcohol flushing for subsurface remediation
- ENA enhanced natural attenuation (with H_2O_2)
- Feasibility studies for ISCO and Nano Iron Injection

He is involved in some national engineering societies as leader of workgroups (ITVA, Ingenieurtechnischer Verband für Altlastenmanagement und Flächenrecycling e.V., altlastenforum af). He is the academic representative in the steering group of NICOLE. Currently he acts as coordinator of a large EU-FP7 project (28 partners, 4 years, 14 Mio €) called NanoRem: Taking Nanotechnological Remediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment.