Investigation of the effects of groundwater resurgence and subsequent exfiltration of ferrous groundwater from the dump site of the Witznitz former lignite mine into the Pleisse and Wyhra rivers

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Abstract

Decades of open-cast lignite mining and groundwater lowering have substantially affected the landscape and hydrogeology of the South Leipzig Region. The overburdens of the opencast mining industry in Saxony mostly contained pyrite, which had to be excavated and dumped. After the closure of the mining industry, groundwater resurgence started and pyrite weathering was initiated, leading to acidification and accompanying mobilization of acidity, iron and sulfate through direct and indirect diffuse groundwater inflows into the water courses. The study presents a remediation measure for the reduction of acid, iron- and sulfate loaded groundwater leachates from the Witznitz lignite dump site into the Pleiße River. Embedded in a monitoring and modelling investigation program, different remediation approaches were examined to minimize negative impacts on the aquatic ecosystems. According to groundwater modelling results, an influx of around 935 kilogram of iron load per day have entered the Pleiße River through diffuse groundwater exfiltration from the balance areas of the dump site of Witznitz in 2009. In order to reduce the exfiltration volume of ferrous groundwater from the Witznitz dump site an optimized and adapted land cultivation scheme for post-mining landscapes has been tested since 2009. The aim was to minimize the amount of percolation water and thus to reduce groundwater recharge quantities. Thereby a comparison between cocksfoot *(dactylis glomerata)*, lucerne (*medicago sativa)* and reference crops indicated that lucerne performed promisingly in regard of reducing percolation quantity as well as having high yields. Based on these positive results, a large-scale experiment was developed and implemented starting in 2014, in which 225 hectares were planted with lucerne. In addition, the plausible impact of the large-scale experiment was estimated through the application of a reactive groundwater flow and transportation model, which showed that in the long term a groundwater discharge reduction of 33, 40 and 34 percent could be attained through the tested counter-measure in 2027, 2040 and 2100 respectively. This in turn should lead to an iron load reduction of approximately 342, 433 and 324 kg/d respectively, accounting for around 1/3 of total iron influx from the Witznitz dump site. Further evidence of the effectiveness of the measure has to be evaluated during the forthcoming years.

Key words: post mining landscapes, lignite, iron, groundwater exfiltration, remediation measure, land use conversion

Introduction

For many decades the landscape of the South Leipzig Region has been shaped by intensive lignite mining. During the mining activities an enormous artificial lowering of the groundwater table by pumps was made and large amounts of overburden and spoil were generated. Through the movement and disintegration of unconsolidated rocks (from depths of up to 60 meters) pyrite oxidation processes were initiated and large quantities of iron oxides and sulfate have been, and are still being, generated. Consequently, a massive intervention involving the surface and subsurface water catchment areas has been put into place. Whereas most of the site remediation measures above ground are completed, there are still major efforts required to remedy appropriately the long term impacts from mining-impaired areas - which are increasingly affecting the water quality of the catchment areas that have rising groundwater levels and groundwater inflows. Therefore, the diffused sources of groundwater inflow into the rivers and post-mining lakes as well as the long-term nature of the problem) require a high level of reliable data to help devise appropriate and effective countermeasures.

In 2003, an ochre coloring of the Pleiße River was observed. Ochre colored water streams and the accumulation of iron hydroxide sludge indicate the effects of groundwater exfiltration with high loads of soluble ferrous iron and insoluble ferric iron into a water course. The unpleasant coloring of the water leads to negative impacts on the recreational and touristic use of the watercourses as well as to impairments of the aquatic communities of fish, macrozoobenthos and macrophytes. In absence of appropriate additional countermeasures the continuous discharge of acid iron- and sulfate compounds would last even beyond the 24th century (IBGW 2010). In accordance to the German Federal Mining Act the Lausitzer und Mitteldeutsche Bergbauverwaltung GmbH (LMBV) has the obligation to remediate the former opencast mining sites in East Germany. For the clarification of the complex issue an investigation framework was developed and a pilot project entitled “Investigation of the effects of groundwater resurgence and subsequent exfiltration of ferrous groundwater from the dump sites of the former Witznitz lignite mine into the Pleisse and Wyhra rivers” was set up by the LMBV in 2007. The project area and an image of the ochre colored Pleiße River is shown in *Figure 1*.

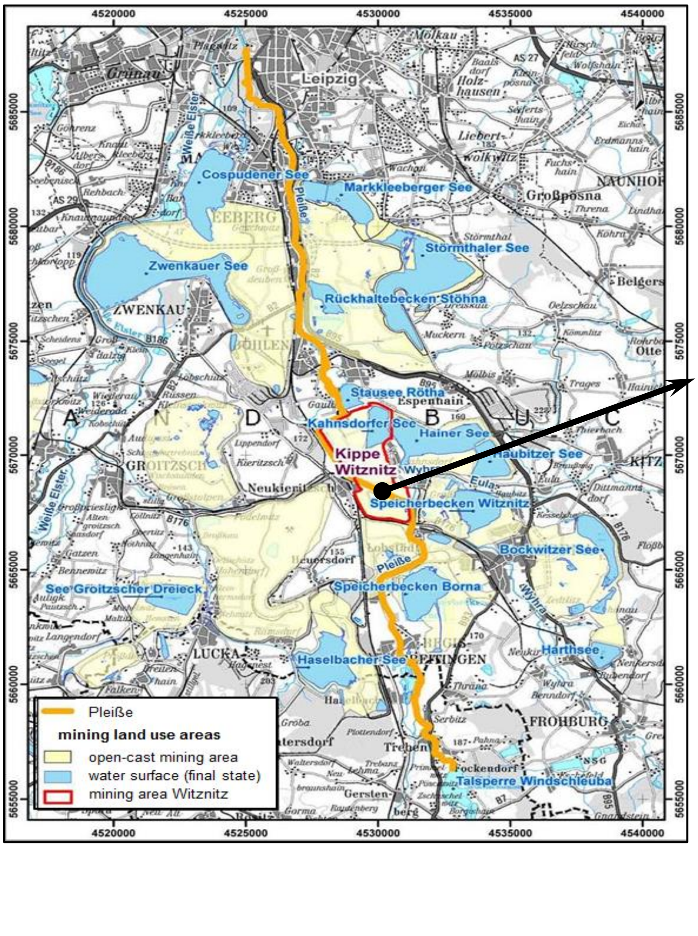
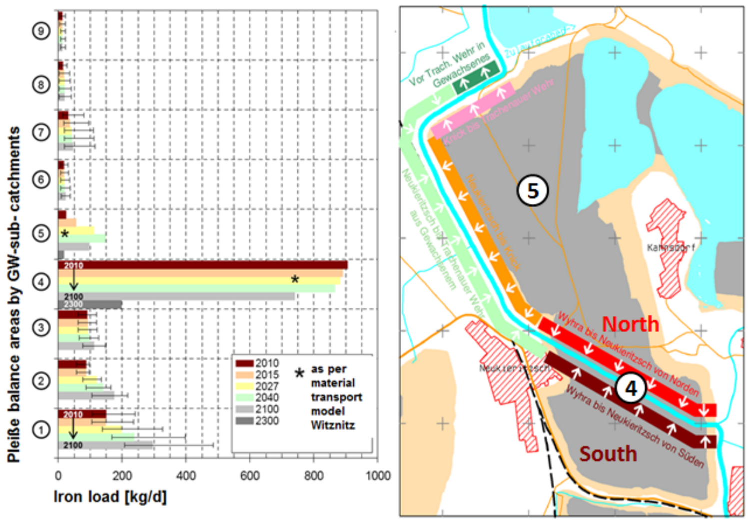


***Figure 1** Location of the project area and lignite mining districts of the South Leipzig Region, Surveyed Area and Pleiße River Monitoring (orange), the Witznitz dump site (red framing, study site) and an image of the ochre colored Pleiße (right) (IBGW 2009)*

Pilot project - Approach and baseline conditions

The overall aim of the project was the detection, evaluation and prediction of the diffuse sources of acid iron and sulfate substance flows and quantities in order to determine appropriate and economically feasible measures for immediate and medium-term hazard prevention and improvement of the water quality in the catchment area of the Pleiße River. Furthermore, a transfer of the applied conceptual framework and of the key project outcomes to other locations of the region with similar problems was desired. The investigation, monitoring, evaluation and implementation steps of the project were organized within three phases, and from the outset of the pilot project, the involvement of a range of institutions and authorities was enabled through the establishment of a working group under the leadership of LMBV, as the agency executing the project. Thus, since 2008 a monitoring program has been in operation to observe and document constantly the water quality and sedimentation quantities along the Pleiße River. Additionally, the groundwater level and quality was measured. Parallel to this, a groundwater flow and substance transport model was set up for the Witznitz mining area through the utilization of the available geological data, mine plans, groundwater monitoring results and water quality monitoring results from the Pleiße (IBGW 2009, 2009a, 2010). Consequently, the water course was subdivided into respectively nine groundwater balance areas, whose groundwater exfiltrates from the eastern and western sides into the Pleiße. Based on these data sets the localization and quantification of the hot spots of the diffuse iron-loaded groundwater inflow was determined and it was confirmed that the highest loads of iron enter the Pleiße River directly from the groundwater inflow of the former Witznitz mining area. The iron concentrations at this section of the Pleiße River are ranging between average values of 3 to 6.5 mg/l, whereas higher concentrations were detected during low and medium runoffs (IBGW 2009, SLG 2014).

In *Figure 2* the results of the model calculations of groundwater discharge volumes and iron loads are presented. In 2009 an average iron load of 935 kilogram has been exfiltrated from the Witznitz dump site into the Pleiße River per day. This corresponds to 55 percent of the total iron load of the investigated catchment areas. According to the simulation model, the iron loads of the balance area 4 (South and North) are by far the most significant (917 kg/d). In regard to the groundwater discharge volumes, the stationary state of the balance area 4 North was almost achieved in 2009, whereas for the balance area 4 South an increase from 0.23 m³/min to 0.35 m³/min until 2100 is predicted. The total iron load from the Witznitz dump site (balance area 4 and 5) was estimated with around 1000 kg/d until 2100 and it was projected that it will decline to around 250 kg/d until 2400 (IBGW 2009b, *IBGW 2010)*.



	Groundwater discharges from the Witznitz dump site into the Pleiße River			
	2009		stationary state	
balance area	m³/min	%	m³/min	%
4 South	0.23	37	0.35	45
4 North	0.15	24	0.17	22
5	0.21	34	0.22	29
5	0.03	5	0.03	4
total	**0.62**	**100**	**0.77**	**100**

	iron loads according to balance area		
	4 South	4 North	
GW-discharge into the Pleiße 2009 in [m³/min] or [l/s]	0.23 or 3.8	0.15 or 2.5	1.12 or 19
discharge concentration [mg/l] Median Min-Max	1230 (900-2800)	2360 (2140-2420)	11 (10-22)
iron loads in [kg/d] Median Min-Max	407 (300-930)	510 (460-520)	18 (16-35)
total iron loads in [kg/d] Median Min-Max	935 (770-1480)		
GW-discharge and iron load into the Pleiße 2009	***547 m³/d 917 kg/d***		1613 m³/d 18 kg/d

Figure 2 *Projection results of iron loads entering the Pleiße from the balance areas 1 to 9 in 2010, 2015, 2027, 2040, 2100, 2300 (*as per material transport model Witznitz) (left) (IBGW and Ecosystem Saxonia 2011); Baseline balances of groundwater flow and iron loads entering the Pleiße from the Witznitz dump site between the mouth of the Wyhra and the Trachenauer Weir (right) (IBGW 2009b)*

Description of the Witznitz former lignite mining area

The Witznitz former lignite mining area is located around 15 kilometers south of Leipzig between the villages of Neukieritzsch, Kahnsdorf and Rötha. It was operated in a series of successive stages from 1900 to 1990. The Kahnsdorf Lake belongs to the area and it is an acid mining lake with a depth of around 40 to 60 meters. The area has a size of around 450 hectares and the overall volume of the dump site is around 360 million cubic meters (IBGW 2010). It is situated in a tributary of the Pleiße in the section between river kilometer 23.8 where the Wyhra enters the Pleiße and the Trachenauer Weir at river kilometer 17.5. Because of mining activities, the course of the Pleiße and Wyhra rivers was relocated in a westerly direction so that since the 1960s the Pleiße River flows through the Witznitz dump site. The mean annual runoff at this part of the Pleiße is around 6.5 m³ per second. Preliminary studies indicated that the top soil of the Witznitz post-mining area consists of loamy-silty sands to sandy loam with indications of waterlogging conditions and acidity in the subsoil (FIB 2012, Haferkorn 2011). The land use is dominated by agricultural use (65 %). Furthermore, around 19% of the area is forested, 5 % grassland and 10% ruderal sites (IBGW 2009).

Materials and methods

Aim and Scope

From a set of evaluated remediation measures of the pilot project this study presents the results of a coordinated and scientifically accompanied land use conversion from crop land to quasi permanent pasture on the former dump site of the Witznitz mining area. The general approach of the measures was to establish optimum growth conditions for plants so that an increased evapotranspiration is enabled which leads to a reduction of percolation. Thus, the overall goal was to prove that an optimized land use conversion and adaptive water balance management can lead to a reduction of groundwater recharge considering moderate hydrological conditions. Especially for the study site, it is expected that improved water balance management - i.e. through permanent soil covering - will minimize the groundwater recharge and subsequently induce a decrease of the exfiltration of ferrous groundwater from the Witznitz dump site into the Pleiße River. In Figure 3 a scheme of the theoretical approach of the measure and the system behavior is given.

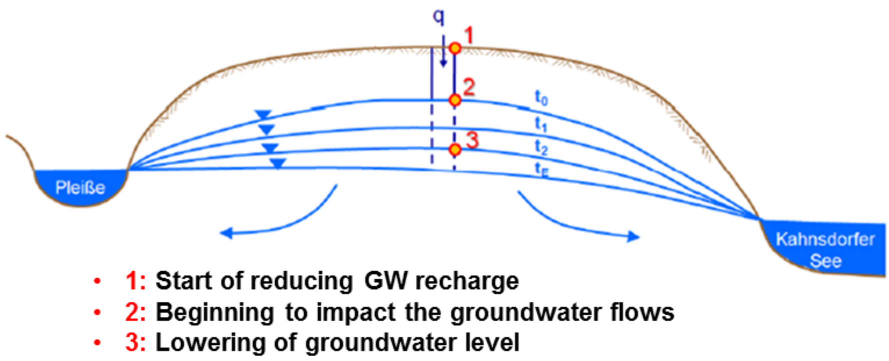


Figure 3 *Theoretical Approach of the measure (GFI 2012)*

Basically, the land use conversion was restricted by the preferences of the landowner. For example a conversion towards forest with high evapotranspiration rates was not welcomed; however, an agreement on the cultivation of perennial energy and fodder crops was reached. From a selection of the testing cultivars, cocksfoot *(dactylis glomerata)* and lucerne (*medicago sativa)* as alternatives to conventional crop rotations (with high share of grains and rape) were chosen. The selection was based on the following criteria: 1. good adaptation to local conditions, 2. reduction of groundwater recharge through strong above- and underground growth, 3. high exhaustion of the soil moisture storage, 4. shortening of the fallow period, 5. positive effects on soil development and fertilization of the post-mining soils, 6. short-term effects on the water balance as well as 7. being suitable for cultivation and harvesting using conventional agricultural technology and 8. the opportunity to integrate the productivity of the land into profitable business processes (FIB 2012).

Experimental set up

From 2009 until the present, field tests were conducted to estimate an order of magnitude for the effectiveness of the proposed measure. During the assessment, optimized cultivation preconditions in regard to fertilization, soil improvement and preparation and their impact on yields and water percolation were tested and evaluated. Overall, six test areas with a size of 20 meters by 50 meters (VF1), four test areas at the side of the mining area (VF2) and six control plots on the agricultural land were installed and tested before a large-scale experiment was carried out in 2014 (L). A detailed overview of the study sites is given in *Figure 4*. In addition to the field tests, two lysimeters on the Witznitz mining area and four prepared lysimeters at the lysimeter station in Brandis and another reference lysimeter were included in the experimental program. In this way, an array of multiple test configurations at the field trials and lysimeter plots could be arranged concurrently. The plot cultivation was organized in a synchronized manner with lucerne, cocksfoot, a mixture of cocksfoot and lucerne and different reference crops like silage maize, winter wheat and winter barley being planted. At the test sites and for the preparation of the monoliths of the lysimeters the following soil enhancement methods were applied: 1. up to 80 centimeters of soil loosening, 2. liming and 3. application of an admixture of 125 or 500 tonnes dry matter from sewage sludge compost per hectare. Depending on the growth height, three to four harvests were made. From the outset, the test field was accompanied through a comprehensive soil-water-plant monitoring program as well as water balance modelling. The monitoring was complemented through laboratory tests and test-related modelling of the percolation quantity considering all site-related water balance components. Thus, the interactions between soil improvement and preparation and its impact on growth and the overall water balance could be investigated (GFI 2012, 2013, 2014, 2015).

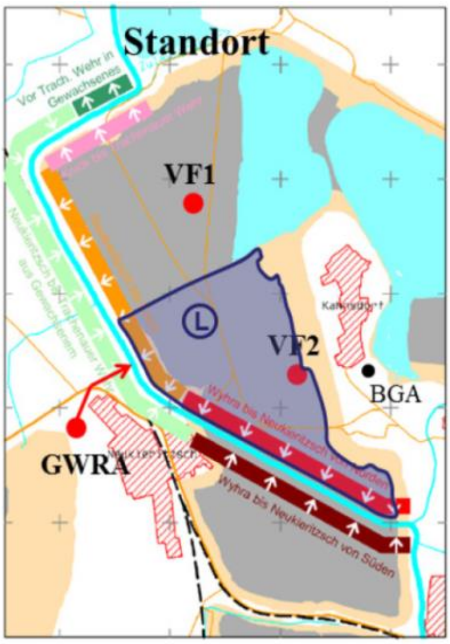


***Figure 4** Sampling sites (VF1, VF2), large-scale experiment area (blue shaded area L) at the former mining area of Witznitz (IBGW)*

Based on promising results of the field test, a concept for a large-scale experiment was proposed, an area of 225 hectares was selected (cf. *Figure 4*) and a cultivation management contract with the land tenant was signed in 2014. The soil preparation was derived from the key findings of the field tests and a soil survey of the agricultural land. The large-scale experiment with a determined crop rotation scheduling will be continued in the long-term (GFI 2015). Soil preparation, maintenance and harvesting will be organized in cooperation with the land tenant.

Results

<u>Comparison of the soil enhancement methods and the annual yields of lucerne, cocksfoot and cocksfoot/lucerne</u>

At the test fields VF1 und VF2 as well as at the lysimeter plots, soil loosening and liming had a positive effect on the biomass production of the cocksfoot and a marginal impact on the yield of lucerne. Also the application of varied admixture of sewage sludge compost influenced positively the biomass production of cocksfoot and had less impact on the growth of lucerne. As cocksfoot had lower yields than lucerne and due to intermediate outcomes that soil improvement through sewage sludge compost application was not feasible because of environmental restrictions a modification of the experimental set-up was applied in 2012. Accordingly, the testing area VF2 was dismantled, the lysimeter monoliths containing sewage sludge compost were set up without sludge and the cocksfoot testing plots were replanted with a mixture of cocksfoot and lucerne. Overall, the lucerne yield remained relatively stable, with an average yield of 12 to 13 tonnes dry matter per year during the test period from 2010 to 2015. For cocksfoot the yield was generally lower and more variable. Depending on the preconditions it ranged between 8 to 10 tonnes dry matter per year. The yield increased to an average of around 10 tonnes dry matter per year when a mixture of cocksfoot and lucerne was cultivated. Generally, the yields at the lysimeter plots were lower than the yields of the test plots and control plots because of drought damage and an island effects. The basic findings of the phenology parameters confirmed that lucerne performed best in regard to biomass production. From an economic perspective, a lucrative utilization of it as an energy crop and fodder crop by the land tenant is possible and thus this remediation measure can be classified as financially self-sustaining (Grontmij 2015, Luckner 2015).

Lysimeter results - Soil-water balance and effectiveness of the measure

In *Diagram 1* and *Diagram 2* an overview of the lysimeter and water balance results for the period from 2009 to 2015 is presented.

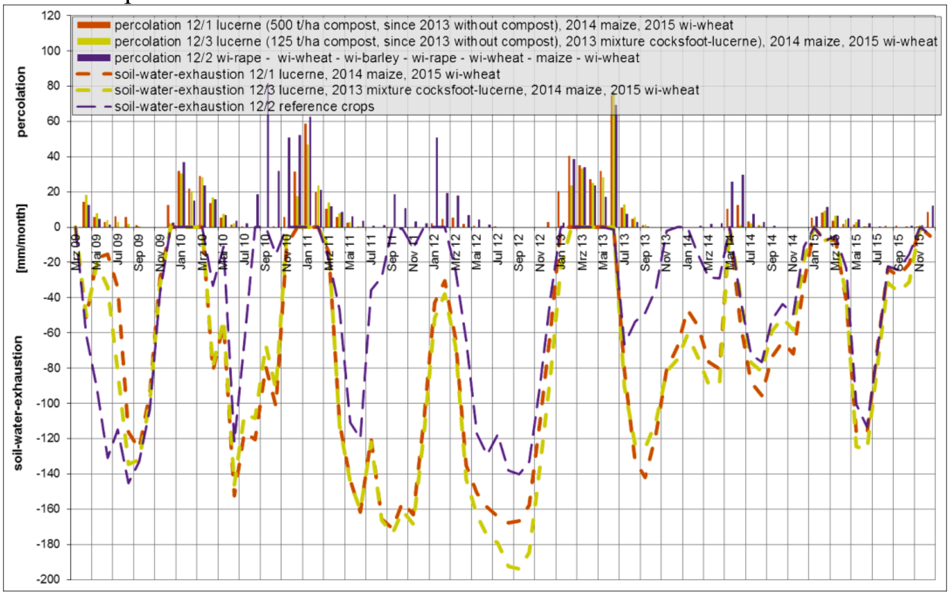


Diagram 1 *Lysimeter results of soil-water exhaustion and quantity of percolation per month 2009 - 2015, Comparison of lucerne, cocksfoot/lucerne and reference crops (GFI 2015)*

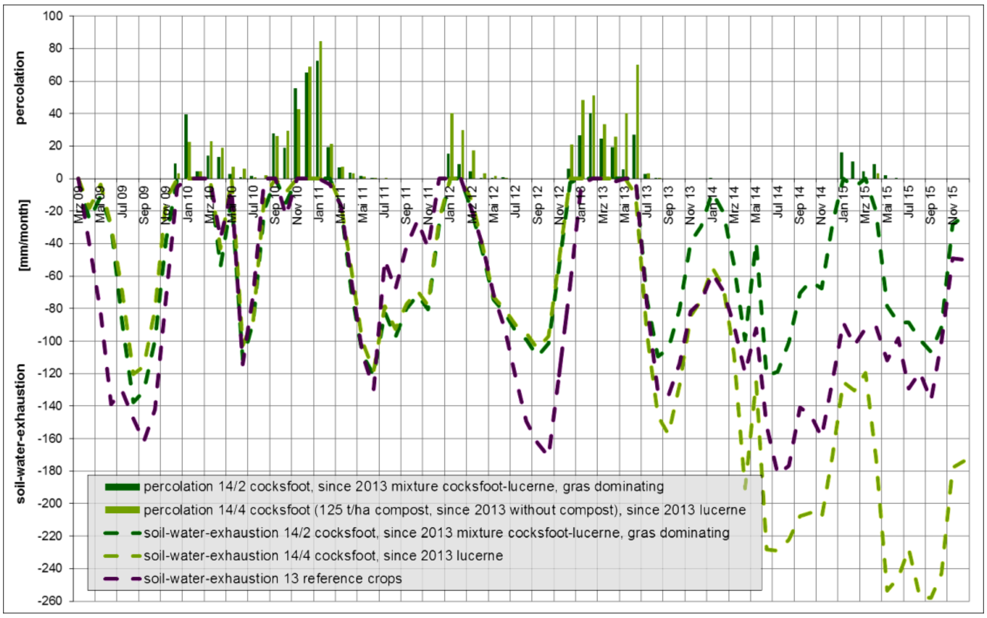
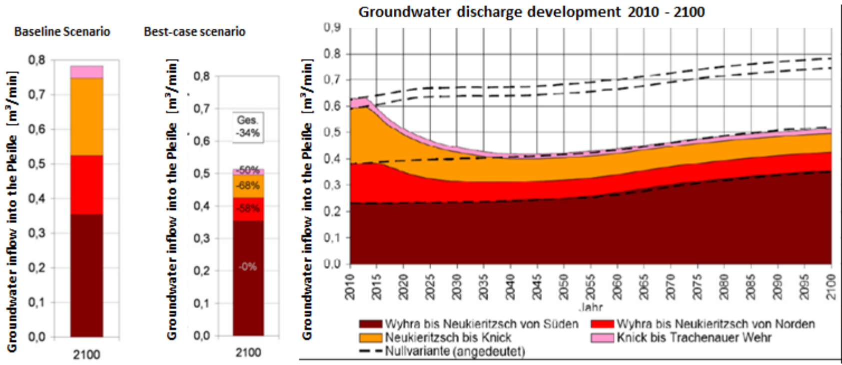


Diagram 2 *Lysimeter results of soil-water exhaustion and quantity of percolation per month 2009 - 2015, Comparison of lucerne, cocksfoot, cocksfoot/lucerne and reference crops (GFI 2015)*

Lucerne was cultivated at the lysimeter plot 12/1 and 12/3 (orange and yellow line) from 2009 to 2012, in 2013 at the lysimeter plot 12/1 (orange line) and since 2013 at the lysimeter plot 14/4 (light green line, cf. *Diagram 2*). In general, it could be observed that lucerne required an establishment phase of around one year and it performed better in summer than in winter months. The highest impact on the soil-water balance and, thus, the highest effectiveness of the measure were especially obvious for the years 2010, 2012, 2014 and 2015 (cf. *Diagram 1* and *Diagram 2)*. In these years, the measured soil-water exhaustion was highest and, thus, induced a reduction of the percolation quantity at the lysimeter plots of lucerne, whereas the percolation volume could be reduced by more than 60 percent in comparison to the reference lysimeter plots (12/2 and 13). Due to high precipitation and the modification of the experimental set-up in 2013 (removal of the sewage sludge compost), another initial phase was required and all lysimeter plots monitored showed almost similar high percolation quantities in this year. However, the monitoring results of the soil-water balance at the lysimeters indicated that a quasi-permanent cultivation with lucerne was most useful in increasing the soil-water exhaustion quantity and, thus, in enabling a reduction in the quantity of percolation compared to cocksfoot, cocksfoot/lucerne and conventional crop rotations.
Based on these results, lucerne became the preferred plant to be cultivated for the large-scale experiment (GFI 2012, 2013, 2014, 2015; FIB 2011).

Projections 2100: Comparison between the baseline scenario and plausible effects of the lucerne large-scale experiment

Assuming that a land use conversion of 225 hectares lucerne cultivation will allow a reduction of 75 percent in the groundwater recharge, a “best-case scenario” was developed and compared with the baseline scenario. In *Figure 5* an overview of the results of a reactive groundwater recharge model for the year 2100 is presented. Based on the stated best-case conditions, the currently implemented large-scale experiment would have an impact on the balance area 4 North and, due to impacts on the groundwater flow, also in part on the balance area 5 (orange and pink). Here, the median iron load at stationary state in 2100 was estimated with 829 kg/d. From this balance area the groundwater discharge volume and iron loads could be reduced by 58, 68 and 50 percent respectively. This in turn would lead to an iron load reduction of around 324 kg/d in comparison to the baseline scenario (IBGW 2010, IBGW and Ecosystem Saxonia 2011). Assuming a 75 percent reduction of the groundwater recharge, the groundwater table in the central part of the Witznitz dump site will decrease by around 6 meters. Thus, the currently implemented large-scale experiment would account for a groundwater discharge reduction of 34 % and an iron load reduction of about 39 percent of the overall load that is entering the Pleiße from the Witznitz dump site.



Scenario Comparison: GW-recharge-reduction at the Witznitz dumpsite				
balance area	4 North	4 South	5 East	5 East
Baseline Scenario 2100				
GW-discharge into the Pleiße 2100 in [m³/min], l/s] and median iron concentration [mg/l]	0.17 2.83 1440	0.35 5.83 757	0.22 4.3 55	0.03 0.5 55
iron load in [kg/d]	353	386	90	
total GW-discharge and iron load	***0.77 m³/min 829 kg/d***			
Best-case Scenario 2100				
GW-discharge into the Pleiße 2100 in [m³/min] and median iron concentration [mg/l]	(-58%) 0.07 1433	(0%) 0.34 716	(-68%) 0.07 49	(-50%) 0.015 49
iron load in [kg/d]	147	348	10	
total GW-discharge and iron load	***0.51 m³/min (-34 %) 505 kg/d (-39%)***			

Figure 5 *Comparison of groundwater discharge development from 2010 to 2100 between the best-case scenario (assuming 75 percent of groundwater reduction through lucerne cultivation on the 225 hectares of the large-scale study area) and the baseline scenario (Grontmij 2015, GFI 2012, IBGW 2010)*

The estimated groundwater recharge reduction for the years 2010, 2015, 2027, 2040 and 2100 is summarized in *Table 1*. Based on the modelling results, the highest groundwater recharge reduction and iron load reduction will be attained in the year 2040. However, a measureable impact can be expected already in the next years.

Table 1: *Groundwater discharge and iron load development for the years 2010, 2015, 2027, 2040 and 2100 and scenario comparison of the plausible impact of a groundwater recharge reduction through lucerne cultivation (adjusted from Appendix 6, IBGW and Ecosystem Saxonia 2011)*

		2010	2015	2027	2040	2100
Baseline-Scenario	[m³/min]	0.62	0.64	0.66	0.68	0.77
	[kg/d]	924	939	993	1009	829
Best-case scenario	[m³/min]	0.62	0.59	0.44	0.41	0.51
	[kg/d]	924	910	651	576	505
GW-recharge-reduction	[%]	0	-8	-33	-40	-34
iron load reduction	[%]	0	-3	-34	-43	-39
	[kg/d]	0	- 29	- 342	- 433	- 324

Discussion and Conclusion

During the last seven years of field studies at the Witznitz post-mining landscape it could be generally confirmed that a land use conversion towards a quasi-permeant pasture cultivated with lucerne allowed a considerable reduction in groundwater recharge in comparison to conventional crop rotation, taking into account moderate hydrological conditions (GFI 2015, Beims et al. 2015). Initial soil loosening, liming and fertilization provided optimized soil conditions for plant growth and the stated culture criteria (strong above- and underground growth, high exhaustion of the soil moisture storage, shortening of the fallow period, positive effects on soil development and fertilization of the post-mining soils, short-term effects on the water balance, self-sustaining) could be confirmed for lucerne. Based on the results of the conducted investigation, a reduction of the ferrous groundwater inflows into the Pleiße River should occur gradually through the applied counter-measure. Thereby, the results of the scenario comparison indicated, that in addition to the very slow natural decline of iron concentrations in the groundwater, a plausible reduction of about 34 to 43 percent (-342 kg/d to - 433 kg/d) of iron load could be attained during the years 2027 to 2100 through large-scale lucerne cultivation. The results highlight that the overall effectiveness of the counter-measure can be regarded as highly efficient.

Further studies in regard to impacts of crop rotation and heavy precipitation are proposed. Here, also additional investigation in regard to the plausibility of peak loads, rebound effects and effects of climate variability and change need to be conducted and evaluated. Furthermore the delayed exfiltration and time dimensions of the problem need to be discussed in greater detail. Finally, the long-term impact of the presented remediation measure has to be proven during the forthcoming years of the large-scale experiment implementation and its actual effectiveness has to become evident through the monitoring results, which will need to indicate a decreasing groundwater table and declining iron concentration in the Pleiße River. The 225 hectares of the large-scale experiment area have been safeguarded for the next few years, and after further adjustments and a denser data set, the knowledge base will increase, enabling a more precise final evaluation of the effectiveness of the proposed and discussed remediation measures to be made. In general, the transfer of the process know-how, implemented methods and tools for the projection of iron loads from groundwater inflows to comparable mining sites is possible after an adaptation to the site specific conditions and clarification of the hydrogeological preconditions. The transfer of the measure depends, amongst other things, on the land use preferences of the landowners.

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