Reduction of seepage outflow from potash tailings piles by improvement of greening: Results of a hydrological simulation

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Abstract
Groundwater and surface water in the Südharz potash mining district are influenced by high chloride salt outflow from waste piles due to leaching, erosion and subrosion. Surface and ground water do not meet ecological standards, especially in terms of the European Water Framework Directive (WFD) as well as German water laws. We elaborated an ecological solution to reduce the percolation water from the five studied piles. For reaching the prior restoration target, to decrease the seepage water formation, a functional combination of mineral coverage system with high water storage capacity and subsequent greening with high evapotranspiration rate is necessary. We assume that complete coverage of potash tailing piles with forest vegetation is able to maximize the evapotranspiration rate. For analyses, the potash tailings piles were subdivided into hydrotopes which are areas with similar hydrological properties. For each hydrotope we collected data of the current vegetation cover and the soil conditions. The results show that about 3.3 % of the potash tailings piles are already afforested and 53.7 % are covered with shrubs, grasses and herbs. The soil conditions are mainly alkaline and cemented by carbonate precipitation. For estimating the effect the percolation water rates (percentage of percolation water on rainfall) of three scenarios of greening were modeled with BOWAHALD: 1) status quo, 2) temporary greening and 3) complete forest vegetation. The hydrological modeling shows only a marginal decrease of percolation water by temporary greening (mean 7 %). Depending on local conditions, a reduction of the percolation water down to 31 to 67 % of the current percolation water is expected by afforestation. In conclusion, complete forest vegetation as a greening concept of potash tailings piles is able to decrease a substantial part of percolation water. However, the formation of seepage cannot be stopped totally and further efforts are necessary to reduce the impact on ground and surface water.

Key words: Potash tailings piles; evaporation of greening; coverage systems; recultivation; chloride charge; water protection

Introduction
Continuous weathering and leaching of potash tailings piles is a long term problem for groundwater and surface water in the Südharz potash mining district around the town of Sondershausen in Thuringia. Due to precipitation, easily soluble chloride is leached by percolation water. Insoluble and slightly soluble components, which mainly consist of anhydrite, gypsum and clay (Schmeisky and Lenz 1998), remain at the pile surface.

In Germany, surface water has to be continuously in a good ecological condition, according to the Water Resources Act of Germany (Wasserhaushaltsgesetz 2009). In the Südharz potash mining district, this standard is difficult to achieve at present. This is particularly true for the river Wipper because of its high chloride charges. This is caused by the catchment’s geology as well as the chloride piles’ drainage water. Retention basins collect a part of the pile’s wastewater and control the release of chloride into the Wipper. The method is insufficient because of the large volume of contaminated pile water, which needs to be diluted in rivers with temporarily low runoff rates and high background salt loads.

A sustainable solution seems to be the avoidance of percolation water formation (Kloss et al. 2014). By decree of the Mining Authority of Thuringia, potash tailings piles have to be covered by a range of materials according to a treatment recommendation (TLUG 2013). While, the recommendation specifies the quality of the cover materials, less emphasis are given to aspects of greening such as tree species selection given the specific conditions on potash tailings piles.

In this study, we developed appropriate greening concepts for five potash tailings piles in the Südharz potash mining district. Our aims were to identify appropriate intermediate and final vegetation types that (1) can deal with the local conditions and (2) reduce the percolation water volume due to increase evaporation rates. For this purpose, we use the BOWAHALD software and assess the percolation water rate of the current and final (complete covered and afforested) conditions for each hydrotope.

Methods

Study site

The five studied potash tailings piles are located in the Südharz potash mining district next to the towns of Bleicherode, Menteroda, Rossleben, Sollstedt and Sondershausen (in the following, the pile's name is identical to the town's name). The pile body mainly consists of sodium chloride (67-77 %). The potash tailings piles Bleicherode, Sollstedt and Sondershausen are located in the Wipper catchment area, while Menteroda is part of in the Helbe and Rossleben of the Unstrut catchment area. Since the German re-unification in 1990, the piles are continuously covered with a mixture of demolition material, sediments, soil and some other non hazardous mineral materials. Currently, the piles surfaces amount to 49.1 ha (Bleicherode), 56.3 ha (Menteroda), 59.8 ha (Rossleben), 57.5 ha (Sollstedt) and 69.1 ha (Sondershausen).

Field sampling

During several field campaigns, we characterized the current vegetation on the piles and surveyed the physico-chemical conditions of the surface materials. Before starting the field sampling, the potash tailings piles were subdivided into "hydrotopes". These are areas with consistent hydrological behaviour. Hence, dissimilarities in geographical direction, vegetation, slope, and soil conditions, which likely result in different hydrological functions, served to group the pile areas into hydrotopes. Aerial photos of the piles from 2011 were used for a first estimation of the vegetation patterns and the degree of coverage. The geographical directions and the slope were calculated using LiDAR-Data (Light Detection and Ranging).

We validated all hydrotope positions in the field and assessed each hydrotope's general vegetation characteristics, in detail. These are most dominant plant species, main and secondary usage in addition to their cover ratio, current and maximum growth high and lushness. Moreover, in a subset of hydrotopes we also determined all plant species and degree of vegetation cover, according to Braun-Blanquet (1964) and Pfadenhauer et al. (1986). For the soil survey, we used a stratified simple random sampling design to take about 20 soil samples at each pile and to conduct in-situ measurements of the saturated hydraulic conductivity with an Amoozemeter. The laboratory assessment of the soil samples included pH value, pore volumes, water holding capacity, permanent welting point and oven-dry density.

Simulation of percolation water rates

For modeling the percolation water rate of each hydrotope we used the hydrological model BOWAHALD (Dunger 2002). The model is particularly suited to simulate hydrological processes on piles. Input data for the model consists of climate data, vegetation parameters, maximal root depth and root density (Kutschera 2010, Kutschera & Lichtenegger 2013), minimal cover degree of seven types of hydrotopes, slope, geographical direction, cover category (six classes linked with soil conditions), saturated water content and values of the laboratory assessment. Furthermore, simulations were run for 13 hydrological years (2001-2013) to get an idea about the annual variation of seepage water formation.

We modeled three scenarios of greening:

- Status quo: This contained the current cover and greening (April/May 2015)
- Temporary greening: This version contained the status quo of cover and greening and an additional greening with *Robinia pseudoacacia, Sambucus nigra* and *Urtica dioica* of all anhydrite areas and hillsides without the final coverage (front disposal)
- Complete forest vegetation: The scenario contained the completely coverage (2 meter of cover material) and afforestation with site-adapted and native deciduous tree species

Results

Soil parameters for BOWAHALD calculation

Values of soil water parameters for anhydrite, debris and earthwork are based on exemplary measurements and soil samples. The following values were used for the model: for anhydrite hydrotopes: saturated water content: 70.9 %, field capacity: 15.8 %, permanent welting point: 15.6 %, k_f-value: 8.33×10^{-5} m/s. For debris hydrotopes: 62.3 %, 30.2 %, 21.5 % and 4.98×10^{-5} m/s. For earthwork hydrotopes: 62.4 %, 30.2 %, 21.5 % and 4.98×10^{-5} m/s. The front disposal hydrotopes were split into two parts. Up to one meter soil depth, we used values of final coverage hydrotopes (different for each pile). From one up to two meters soil depth values of anhydrite hydrotopes were used. The measured values on final coverage are very different between each pile. This is a result of variation in the materials used for the coverage. Table 1 shows the pile-specific soil values used for the model.

Table 1 *Mean of saturated water content [Volume-%], field capacity [Volume-%], permanent welting point [Volume-%] and k_f-value [mm/h].*

	Bleicherode	Menteroda	Rossleben	Sollstedt	Sondershausen
Saturated water content	63.4	58.7	57.1	50.1	62.0
field capacity	30.7	32.5	35.1	34.4	34.3
permanent welting point	16.2	17.2	22.8	22.9	20.0
k_f-value	213.7	95.8	97.4	46.4	125.5

Current coverage conditions

Figure 1 shows the different percentage of the pile's coverage conditions. A precise recording of the coverage was necessary to identify the potentials for further greening.

Current vegetation coverage

The current vegetation coverage could be classified into 1) without vegetation, 2) herbal layer, 3) shrub layer and 4) tree layer. Figure 2 shows the distribution for every pile. Trees and shrubs cover today only a small fraction of the potash tailings piles (Bleicherode: 12.1 ha of 49.1 ha, Menteroda: 4.8 ha of 56.4 ha, Rossleben: 2.9 ha of 59.8 ha, Sollstedt: 8.6 ha of 57.4 ha, Sondershausen: 3.4 ha of 69.1 ha.).

Because of a very eutrophic soil, the shrubs layer is dominated by *Sambucus nigra, Rosa spp., Prunus cerasifera, Crategus monogyna* and *Acer campestre*. The herbal layer mainly consists of *Urtica dioica, Galium aparine, Cirsium arvense, Elymus repens* and *Alliaria petiolata*. Additional, halophytes and other salt tolerant plant species were found on anhydrite hillsides and at the pile's basement (e.g. *Aster tripolium, Gypsophila perfoliata, Lotus tenuis*).

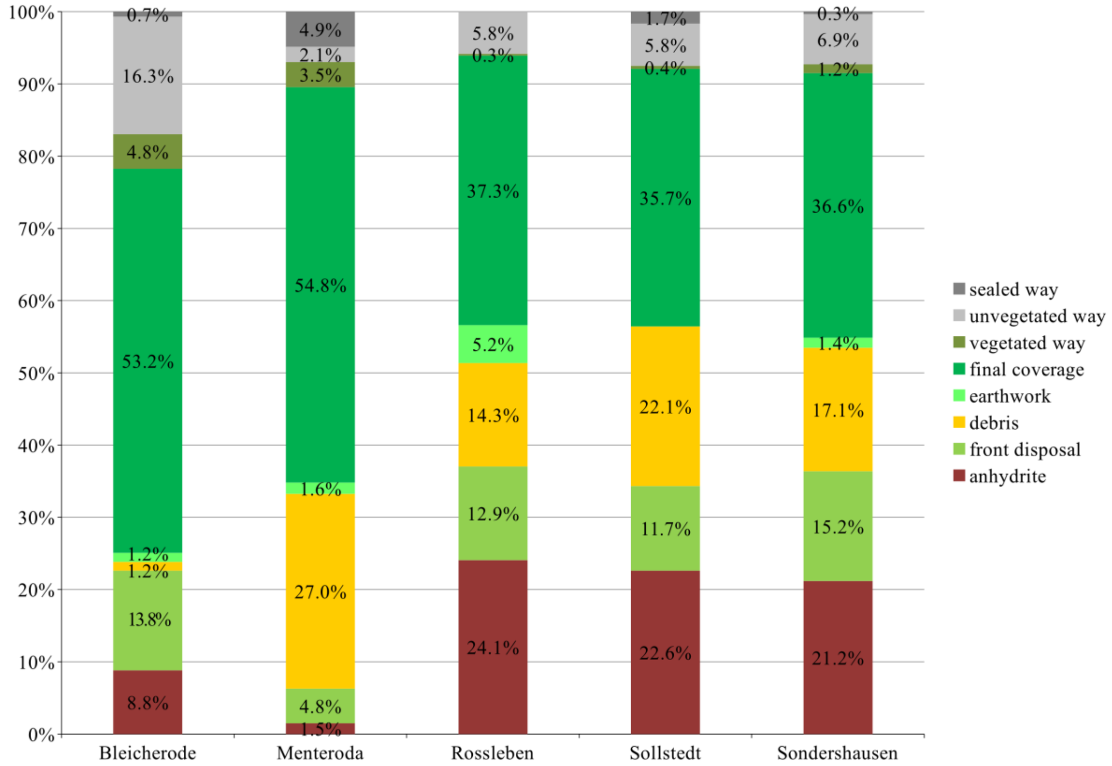

Figure 1 *Percentage of current coverage classes*

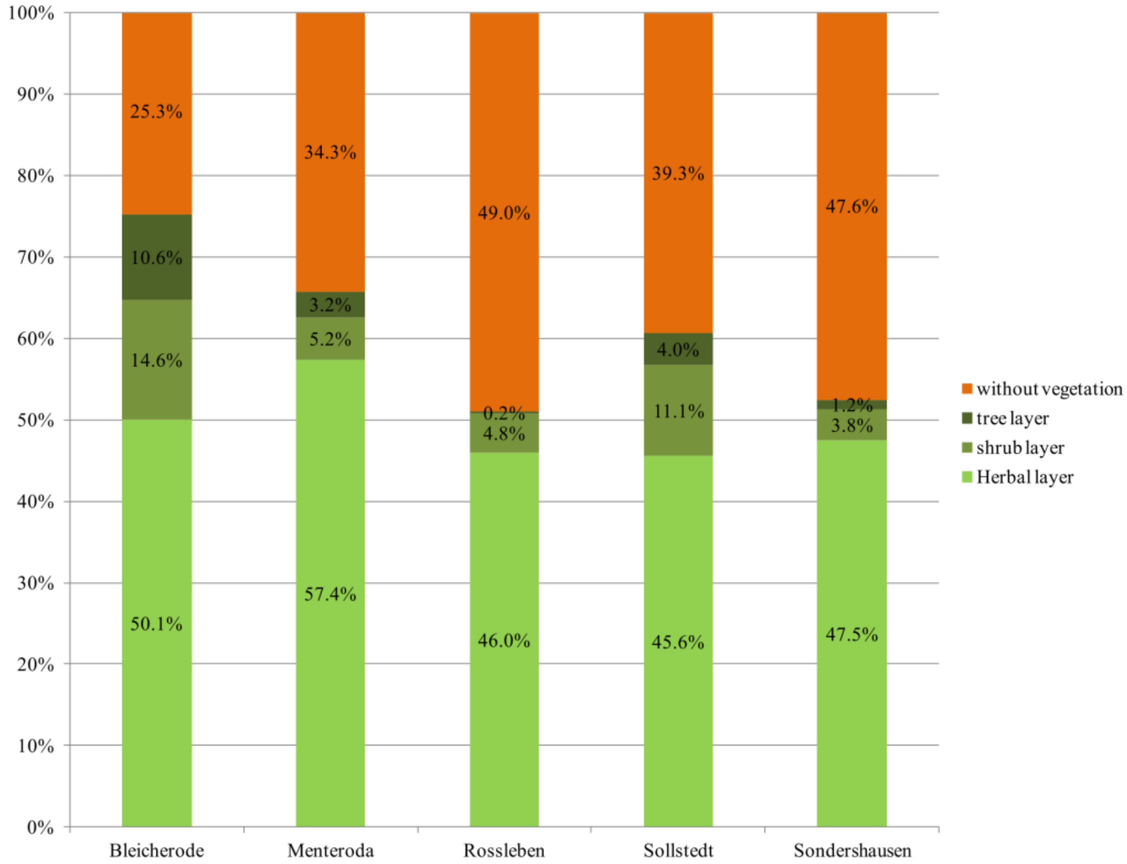

Figure 2 *Percentage of current vegetation cover*

Percolation water rate

In total, the current percolation amount of about 598,000 m³ per year. A temporary greening of anhydrite areas and hillsides with front disposal is able to decrease the percolation water rate by no more than 7 %. In comparison with a final coverage (two meters thickness) and complete forest vegetation a reduction the percolation water volume by 44 % is possible indicating a seepage amount of 335,000 m³ in total per year. Because of the multitude hydrotopes the potential of decreasing can be exactly located upon every pile. Figure 3 shows the median of the percolation share of precipitation for each pile in percentage. Moreover, our dataset allowed mapping the local dispersal of the current and the modeled percolation water rate for every pile. As an example for the maps which were elaborated, figure 4 shows the potash tailings pile Sondershausen.

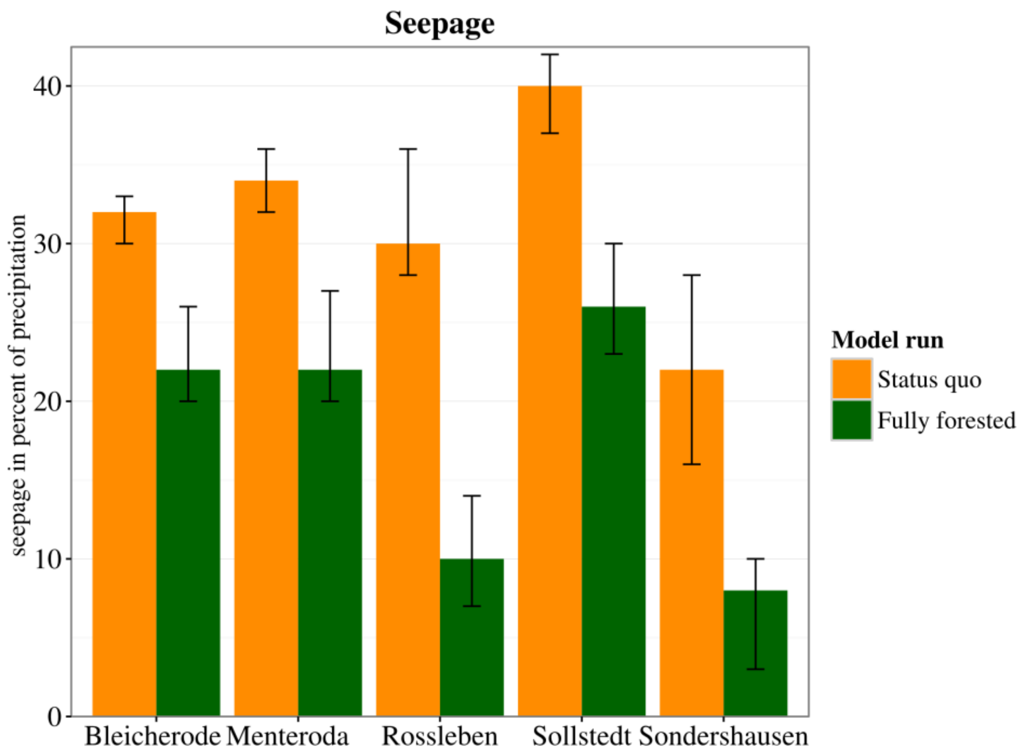

Figure 3 *Current and final seepage in percentage of precipitation, given are the median values. The whiskers represent the range between minimum and maximum.*

Greening recommendation

Out of all single results we derived five greening recommendations. We recommend starting with all final covered areas. The greening ought to start on areas with herbal vegetation, as no preparation is necessary. Secondary, all hydrotops additionally covered by a shrub layer up to 50 % and over 50 %. Within each class of vegetation coverage the calculated decrease of seepage defines the detailed priority list. Finally, trees on all areas with an already existent tree layer will be supplemented. The priority list of areas without the final coverage also depends on the calculated reduction of percolation water amount. Here, the coverage and the greening should begin on hydrotopes with the highest decrease of percolation water.

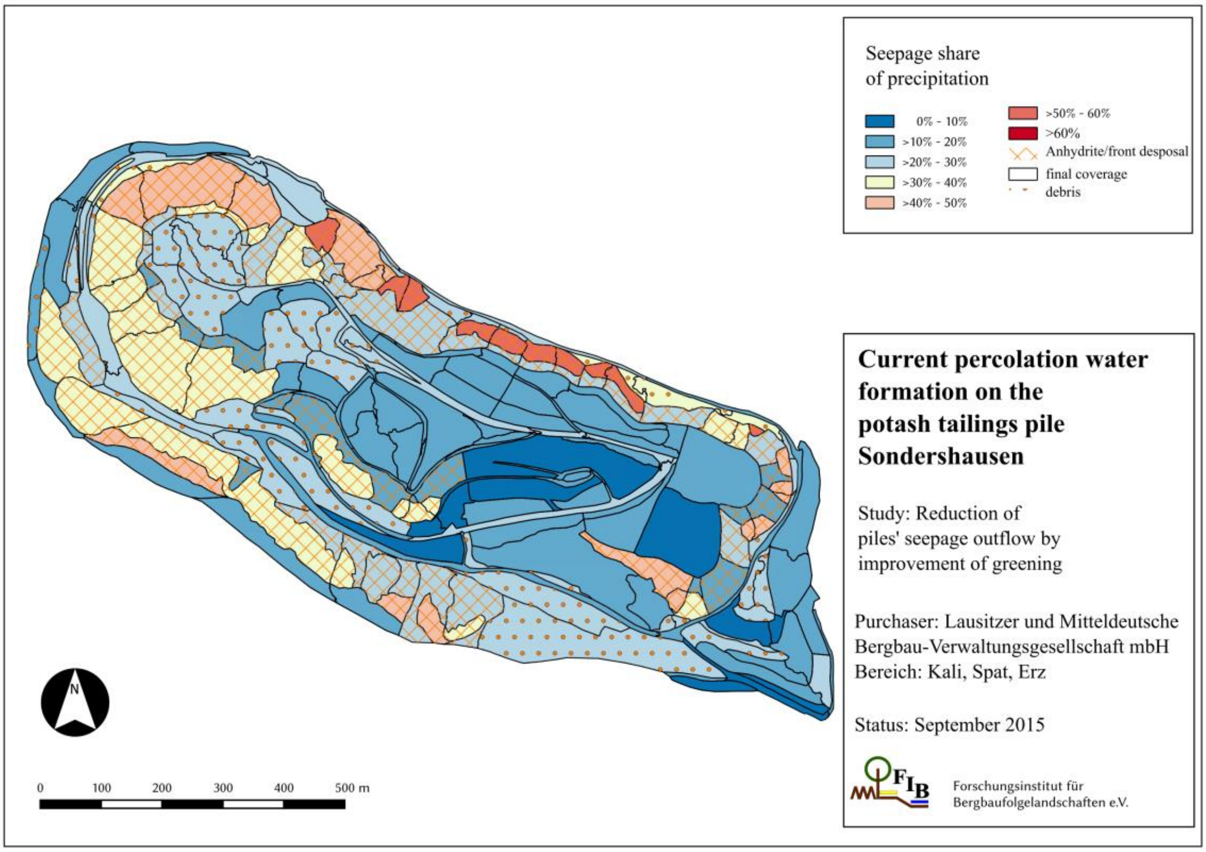

Figure 4 *Seepage in percentage of precipitation (potash tailings pile Sondershausen)*

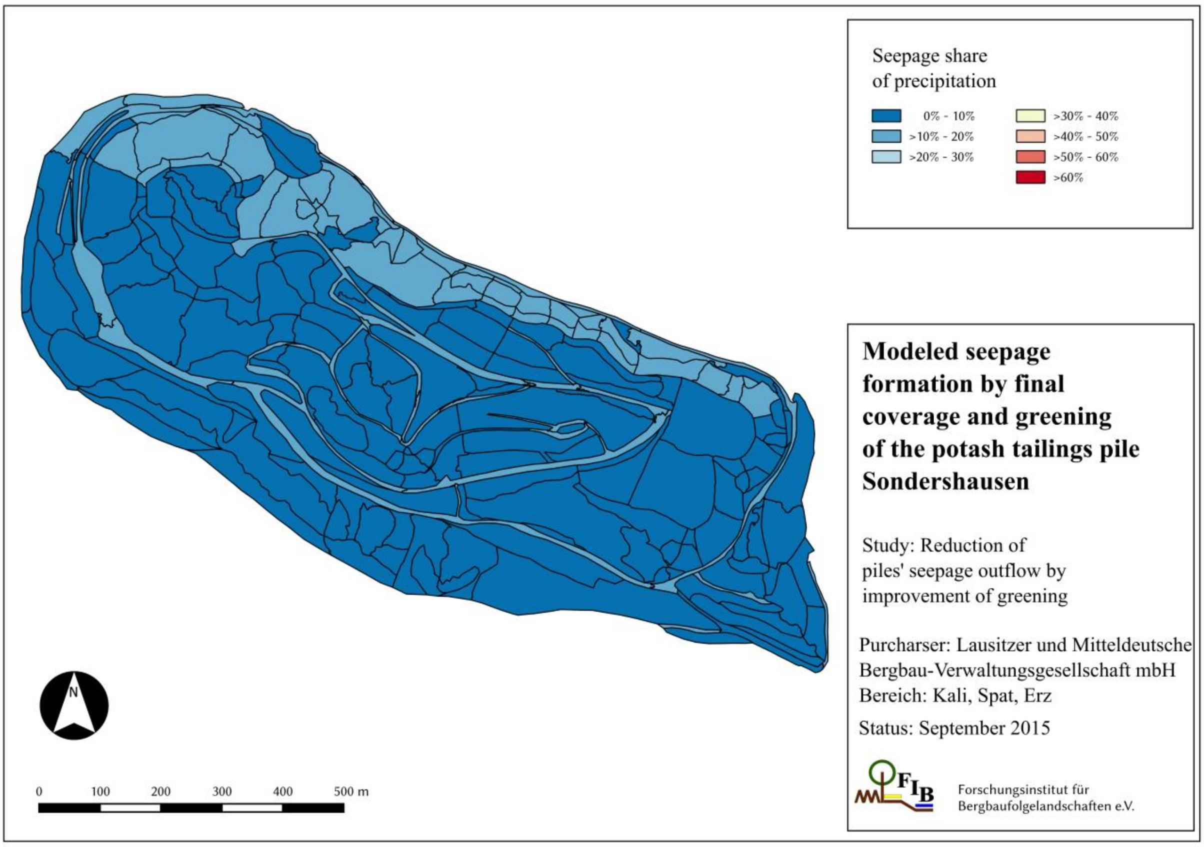

Figure 5 *Final seepage in percentage of precipitation (potash tailings pile Sondershausen).*

Discussion

There are strict regulations for the construction of the coverage system on the potash tailings piles, both for the technical and the soil layer (TLUG 2013). Unfortunately, little is known about the characteristic variables of the soil water storage. Our results about soil characteristics and vegetation conditions provide an indication of water balance conditions of potash tailings piles. Furthermore, we mapped the current stage of coverage and proportion of different vegetation on each of the five piles.

Based on this detailed data, we developed a guiding principle for a protective pile-forest. Compared with the former greening concepts (e.g. Zundel 1991, 1993), high evapotranspiration is the most important target. Further interests like landscape aesthetics or use for recreation are subordinated. Furthermore, the tree composition for the protective pile-forest is adapted to the local soil and climate conditions of each hydrotope.

Seepage water is crucial for the discharge of salts. Earlier research had been undertaken by Stude et al. (2002) with the help of some small lysimeters on the pile Bleicherode. They already modeled the seepage water with the help of BOWAHALD, but the study was restricted to some varying site conditions and vegetation coverage rates. Our study modeled the seepage water for all of the five potash tailings piles, and each of them differentiated into a large number of hydrotopes (altogether 853), based on field data of soil and vegetation.

Our results indicate that 8 to 26 % of precipitation turns into seepage water, even with a complete coverage and a dense protective pile-forest with its closed canopy. There is no guarantee that afforestation indeed reduces the seepage water volume by calculated numbers. The coverage of the piles may locally differ from the intended thickness due to geotechnical restrictions, which cannot be considered. Compared to other landfills, the amount of seepage water appears high. An additional coverage by sealing the surface with plastics here is not applicable, because of ongoing subrosion processes.

A temporary greening results only in a very small reduction of percolation water. Hence, we do not recommend this kind of greening, because of the soil's very low water storage capacity. Heinze & Liebmann (1991) and Schmeisky & Lenz (1998) conducted some early experiments cultivating different plants on only thin coverage or even directly in the anhydrite layer. The growth performance of the plants, selected for high salt tolerance, remained low. Because of the missing soil coverage, this type of greening would not be successful. Our study clearly shows the importance of a water storing soil layer.

Our recommendation focus' on establishing efficient water storing soil layer and target vegetation types with high evapotranspiration.

Conclusions

Our results offer important insights for further recultivation activities. First of all, the regularly prepared soil layers on the top of the mineral covering are suitable for afforestation. The soils are characterized by slightly alkaline conditions and are somewhat cemented. They mainly provide good or sufficient water storage capacity. Based on soil and climate conditions as well as regional presence of tree species, different suitable broad-leaved tree species were selected for an adapted protective pile forest. The hydrological modeling figured out, that a temporary greening has no relevant effect on seepage formation due to the very restricted water storage capacity of anhydrite. We recommend a complete covering and subsequent afforestation with protective pile forests. Depending on local conditions, a reduction of the percolation water down to 31 to 67 % of the current percolation water can be expected. Because all investigated piles are currently lacking any relevant tree or even shrub cover, afforestation with a protective pile forest is the key to maximize evapotranspiration. For direct implementation, we ranked every subarea of the piles relative to its contribution to seepage reduction, both for already covered subareas (where afforestation can immediately start) and for subareas that still need to be covered.

The implementation of our site-specific results in further recultivation are very important for establishing a greening concept, which contains a quickly decrease of percolation water formation from potash tailings piles and salt charge into the nearby catchments.

Acknowledgements

This study was supported by Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV). We thank C. Ertle, T. Heinkele, C. Lange, R. Köhler for collecting the numerous soil samples during the field campaign, B. Krüger for reliable measurements of saturated water conductivity with an Amoozemeter and A. Langer for his always helping hand during the campaign. We wish to acknowledge the pile's owners for allowing us to conduct our field campaign without any problems. We thank V. Dunger for all invaluable references about BOWAHALD.

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