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Final Report 2025

Schäfersee-Verfahren

Support or Remediation of Water Bodies with Oxygen-Depleted Water Layers and Heavily Contaminated Sediments



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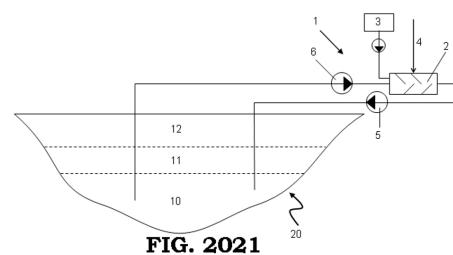
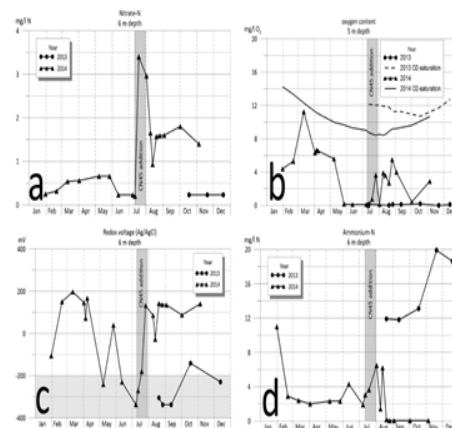


FIG. 2021



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1 Summary

Many standing water bodies in Germany suffer from oxygen depletion and high organic loads. Inputs of nutrients and organic pollutants, particularly from untreated stormwater originating in urban catchments, lead to anoxic sediment zones, accumulation of sludge deposits, and the formation of hydrogen sulfide (H₂S) and methane (CH₄). These processes cause odor nuisance, promote the remobilization of phosphorus and metals, impair benthic communities, and accelerate eutrophication.

The *Schäfersee-Verfahren*® was developed to specifically inhibit these reductive processes. It combines the dosing of calcium nitrate with oxygen-enriched water and links it to continuous online monitoring of water parameters relevant for process control. On this basis, an adaptive *process control* is applied, which regulates dosing as required, stabilizes the redox environment, and deliberately directs microbial turnover. As a result, sulfate reduction as well as H₂S and CH₄ formation are largely suppressed, while phosphorus is retained in the sediment and partially bound in mineral form. The method operates resource-efficiently and in a climate-neutral manner, enabling precise and automated control of in-lake processes.

Within the research project, stationary systems were developed and tested in three different types of water bodies — Schäfersee and Fennsee (Berlin) as well as Jörne Meerke (Neuss). The results demonstrate a significant stabilization of redox conditions, a decline in hydrogen sulfide and methane formation, and reliable phosphorus retention in the sediment. Accompanying analyses by TU Berlin revealed a shift in the microbial communities toward oxidative and denitrifying processes, along with a decreasing trend in methanogenic organisms. Despite the presence of sediment contamination with (semi-)metals and organic pollutants (PAH, TPH, EOX), no relevant mobilization of hazardous substances was observed; under the established oxidative conditions, concentrations of organic compounds tended to decrease.

The *Schäfersee-Verfahren*® thus represents a novel, data-driven instrument for supporting eutrophic and contaminated water bodies. It enables the long-term maintenance of stable, oxidative conditions without the use of energy-intensive aeration or sediment removal and contributes to the reduction of climate-relevant emissions.

The results presented in this report combine the contributions of both applicants — Büro Wassmann and the Technical University of Berlin, Department of Environmental Microbiology. Report Part II was prepared as a joint results report and integrates the field-based, physicochemical, and microbiological findings of the overall project in a consolidated form.

2 Subject and Objectives of the Project

2.1 Problem Statement

Lakes and standing water bodies in temperate climate zones are highly dynamic ecosystems whose oxygen balance responds sensitively to temperature, nutrient inputs, and stratification. Numerous studies over recent decades have documented a marked decline in oxygen concentrations in both surface and deep-water layers (Carey, 2023). The main drivers are anthropogenic eutrophication, rising water temperatures, and hydrological changes that lead to prolonged stratification and an increasing expansion of anoxic zones (LaBrie *et al.*, 2023; Dugener *et al.*, 2023). Eutrophic, urban-influenced water bodies with high inflows from stormwater and road runoff and limited mixing are particularly affected. In such systems, summer warming and high nutrient loads promote stable stratification and massive oxygen consumption in the hypolimnion.

Under oxygen deficiency, microorganisms resort to alternative electron acceptors to sustain their energy metabolism. Nitrate (NO_3^-) is utilized first, though it is naturally available only in limited amounts. Its reduction proceeds via intermediates (NO_2^- , NO , N_2O) to elemental nitrogen (N_2), which is environmentally benign. Once this natural nitrate reservoir is depleted—something that occurs rapidly in eutrophic and warm waters—other electron acceptors such as sulfate (SO_4^{2-}), carbon dioxide (CO_2), or metal oxides (Fe(III) , Mn(IV)) take over in microbial metabolism. These reductive processes lead to the formation of hydrogen sulfide (H_2S), methane (CH_4), ammonium (NH_4^+), and dissolved metal ions.

This shifts the redox balance at the sediment–water interface from an oxidative, stabilizing to a reducing, unstable phase. The consequences are sludge accumulation, the release of contaminants, and the mobilization of nutrients. Phosphorus, which under oxic conditions is bound to iron or manganese compounds, is released under reducing conditions and again becomes available as an internal nutrient source—creating a self-reinforcing cycle of oxygen depletion, substance release, and accelerated eutrophication.

Conventional restoration measures such as aeration, chemical precipitation, or dredging are of limited effectiveness under these conditions. Aeration systems face physical limits because oxygen is only sparingly soluble at higher temperatures and scarcely diffuses into the sediment. Chemical phosphorus precipitation with aluminum-, iron-, or lanthanum-based agents (e.g., Bentophos®, Phoslock®) can bind phosphorus but does not change the redox environment. Even if chemical fixation persists under reducing conditions, anoxic and sulfidic conditions remain in the sediment. The milieu thus remains inhospitable; hydrogen sulfide and methane formation continue, and sludge keeps accumulating.

A sustainable restoration therefore requires approaches that not only bind substances but also *fundamentally stabilize the biogeochemical environment* and restore natural microbial oxidation processes at the sediment–water interface.

2.2 Approach of the Schäfersee-Verfahren

The Schäfersee-Verfahren® was developed to deliberately interrupt the described reductive process cycle in impaired water bodies. The concept is the controlled provision of nitrate in combination with oxygen, thereby reactivating and maintaining microbial oxidation pathways at the sediment–water interface.

The central insight is that nitrate (NO_3^-) is the preferred electron acceptor under anoxic conditions, provided it is present in sufficient quantity. By adding calcium nitrate ($\text{Ca}(\text{NO}_3)_2$), the natural but quickly depleted nitrate buffer is extended, thereby specifically supporting the oxidative metabolism of microbial communities. Denitrification yields elemental nitrogen (N_2), which escapes to the atmosphere without further reactivity. At the same time, sulfate reduction and methanogenesis—processes responsible for toxic gas formation and nutrient release—are effectively suppressed.

The method does not alter natural biogeochemical mechanisms but rather *stabilizes and amplifies* existing oxidative processes that are fundamentally present in the system but weakened or entirely stalled under stress conditions. Controlled nitrate supply keeps the redox potential in the sediment stably positive, eliminates hydrogen sulfide (H_2S), and promotes microbially mediated degradation of organic matter.

A key unique feature of the Schäfersee-Verfahren® is its *process-oriented control*: dosing of calcium nitrate is not constant but based on continuous online measurements of key parameters such as oxygen, redox potential, and nitrate concentration. The readings are captured in real time, evaluated, and automatically translated into control commands for the dosing unit. In this way, a closed control loop is established that actively stabilizes the biogeochemical state of the water body.

This adaptive control strategy fundamentally distinguishes the method from conventional restoration measures. Whereas classical approaches react to disturbances, continuous process control enables *anticipatory regulation* of the water body's condition. As a result, the system can be dynamically adjusted even under changing environmental conditions—after heavy rainfall, temperature increases, or stratification breakdowns.

The Schäfersee-Verfahren® thus represents a paradigmatic approach to modern aquatic therapy: it integrates ecological processes with engineering-based control technology and, for the first time, enables *active control* of redox conditions in real time. Through the integration of sensing, data analysis, and automated dosing, a permanently stable, resource-conserving, and ecologically compatible treatment of eutrophic waters is achieved.

2.3 Project Objectives

The objective of the research project was the development, testing, and scientific evaluation of a process-controlled method for stabilizing anoxic water zones. The Schäfersee-Verfahren® aimed to demonstrate

that, by targeted provision of nitrate in combination with oxygen, permanent redox stabilization—and thus ecological regeneration—is feasible even in heavily burdened systems.

The focus was not the classical reduction of external nutrient inputs but the *reactive treatment of the deep-water body and the sediment–water interface*. There, microbial oxidation processes were to be specifically stimulated and stabilized in order to:

- prevent the formation of toxic substances such as hydrogen sulfide (H₂S) and methane (CH₄),
- promote microbial degradation of organic substances and accelerate sludge decomposition,
- and, in the long term, establish an oxidizing, ecologically stable environment in the hypolimnion.

Beyond immediate restoration, the approach aimed to strengthen the *resilience of the treated waters*—that is, their ability to return to a stable, oxidizing state after stress events such as heavy rainfall or high organic loads.

The question of phosphorus retention and release was not a central research focus at the start of the project, but it gained increasing importance as work progressed. Initial measurements showed that stabilizing the redox environment not only prevented the formation of reductive gases but also led to a clear decrease in dissolved phosphorus fractions. This revealed an additional, originally unexpected pathway of action, which was subsequently pursued through complementary geochemical and mineralogical investigations.

A further central goal was the *technical implementation as an automated, sensor-supported system*. To this end, stationary installations with continuous online recording of oxygen, redox potential, nitrate, and other key parameters were to be developed to enable demand-driven dosing in real time. The development of such an *active process control*—linking measurement, evaluation, and regulation of water treatment in a closed control loop—constitutes a novel approach in aquatic therapy.

In addition, the data and experience gathered in the project were intended to:

- quantify the biogeochemical mechanisms of nitrate dosing,
- evaluate the transferability of the method to different water body types (deep lakes, shallow waters, stormwater retention basins),
- investigate ecological compatibility and possible effects on flora, fauna, and microbial communities,
- and assess the *climate relevance* of the method through suppression of methanogenic processes.

The project thus aimed at establishing a *scalable, resource-efficient, and ecologically compatible remediation method* that allows the long-term stabilization of heavily burdened urban and industrial waters without resorting to invasive or chemically irreversible measures.

2.4 Planned Demonstration Water Bodies

For the demonstration and validation of the Schäfersee-Verfahren®, various types of water bodies were to be considered that exemplify typical stress situations in urban and industrial contexts. This included a combination of a long-term reference lake, a large-scale industrial water body, and additional urban waters with specific problem settings.

- **Schäfersee (Berlin):** Schäfersee forms the project's reference water body. Located in central Berlin, it is heavily impacted by stormwater inflows from a disproportionately large catchment (over 240 ha with only 4.5 ha water surface). Over decades, sludge layers up to two meters thick have formed, causing year-round oxygen depletion in the hypolimnion. As a result of reductive processes, methane and hydrogen sulfide formed regularly, accompanied by toxic effects and the release of phosphorus from the sediment. Partial dredging of the littoral zone down to approx. 3.5 m depth was carried out about ten years ago; however, the deep sediments are considered non-removable for cost reasons. Continuous investigations have been underway since 2013, and since 2017 the lake has been permanently supported by the Schäfersee-Verfahren®. Owing to this long time series, Schäfersee is particularly suitable as a scientifically valuable reference object, even if a classical “before–after” effect can no longer be depicted.
- **Industrial Water Body (Lower Saxony) – Preliminary Investigation, Not Implemented:** As a complement to the reference water body, an additional, industrially influenced comparison site in Lower Saxony was initially planned for a larger-scale demonstration. The water body exhibits pronounced sediment contamination with anoxic zones and hydrogen sulfide formation and was therefore considered a suitable model site for assessing transferability of the method. In 2021 and 2022, extensive preliminary investigations were conducted there, including measurements of oxygen, redox, and nutrient profiles as well as sediment sampling. The installation of a stationary system for continuous dosing and aeration was planned. However, due to missing official permits and administrative requirements, technical implementation could not be carried out. The measurement data and conceptual experience gained in this phase were used for the further development of control strategies and formed an essential basis for the subsequent system implementations at Fennsee and Jörne Meerke.
- **Flughafensee (Berlin) – Assessed, but Not Implemented:** As an alternative to the originally intended site, Flughafensee in Berlin was considered. This roughly 30 ha, up to 35 m deep water body receives substantial stormwater inputs via the Schwarzen Graben and is considered highly burdened. In particular, the approximately 3 ha pre-basin in the northeastern inflow area, with a maximum depth of around 14 m, regularly shows high nutrient levels and pronounced anoxic conditions. This section is partially separated from the main lake by a so-called algae barrier and thus forms a hydraulically distinct basin comprising about one tenth of the lake's total area. This section also contains an aeration system that has been in operation for decades, the

infrastructure of which would have enabled comparatively straightforward technical integration of the Schäfersee-Verfahren®. Scientifically, the site would have been particularly suitable because a clearly delineated, deep hypolimnion offered itself for targeted treatment. However, the project could not be implemented within the intended timeframe.

- Replacement Sites – Jörne Meerke (Neuss) and Fennsee (Berlin):** After neither the industrial water body nor Flughafensee could be realized, two new demonstration sites were secured as part of a project extension. The *Jörne Meerke* is a predominantly shallow excavation lake (3–4 m) that nevertheless features a depression up to 8 m deep. It was precisely in this deep zone that reductive conditions with hydrogen sulfide formation and significant phosphorus release from the sediment regularly occurred. The aim was to dissolve this toxic deep zone and sustainably stabilize the redox potential. The *Fennsee* in Berlin, by contrast, is a stormwater retention basin only up to 3 m deep that is heavily loaded with road runoff. Due to the absence of stratification, sludge processes occurred throughout the entire water column, so that the odor of hydrogen sulfide was perceptible in the surrounding area. Treatment therefore focused on surface-near, event-driven dosing. With these two sites, different problem types (localized deep zone versus shallow basin) could be addressed, demonstrating the applicability of the method across a broader range of water bodies.

2.5 Climate Relevance

The water bodies investigated in the project belong to heavily burdened, eutrophic systems that regularly develop anoxic conditions in deep waters. Under these reducing conditions, large quantities of methane (CH₄) are produced in the sediments, which can escape to the atmosphere via diffusion and, in particular, via gas bubbles (*ebullition*). Such waters are therefore considered significant sources of climate-relevant greenhouse gases, especially in temperate latitudes where numerous smaller and shallower lakes exhibit high specific emissions (Aben *et al.*, 2017).

Methane has a significantly higher greenhouse effect than carbon dioxide (CO₂). In climate reporting, this is expressed by the *Global Warming Potential* (GWP), which compares the warming effect of a gas over a defined period with that of CO₂. Typically, a 100-year (GWP₁₀₀) and a 20-year horizon (GWP₂₀) are considered. According to IPCC AR6, the GWP₁₀₀ for methane (fossil) is about 29.8 and the GWP₂₀ about 82.5, each accounting for climate-carbon feedbacks (Intergovernmental Panel on Climate Change (IPCC), 2023; Howarth, 2024). These values underscore that methane exerts a disproportionately strong climate impact in the short term.

The measures carried out in the project therefore aim not only at ecological stabilization of the waters but also at reducing greenhouse gas emissions by suppressing methanogenesis. Establishing a permanently oxidizing environment at the sediment-water interface effectively prevents the formation and release of methane and thus contributes to the climate relevance of the measure.

2.6 Innovation Core of the Schäfersee-Verfahren®

The distinctive feature of the Schäfersee-Verfahren® lies in the combination of calcium nitrate (CN45) with oxygen-enriched water and a continuous, online-controlled dosing logic. Treatment is process-oriented: only as much is applied as is required at that moment based on the measurement data.

This clearly distinguishes the method from classical, one-off chemical applications or unspecific aeration measures. The technical implementation as a stationary installation (shore-side container, storage tanks, underground pipelines, automatic control) is intended to ensure that durable and resource-efficient application at municipal scale is feasible.

Beyond supporting ecologically stressed urban waters, the method offers potential for industrial use as well as for reducing climate-relevant emissions from inland waters.

2.7 Patent and Intellectual Property Situation

The method is registered in Germany as the trademark *Schäfersee-Verfahren*®. The technical protection is based on the international patent “Remediation and/or restoration of an anoxic body of water” (PCT/EP2017/057041), filed by Yara International ASA. Through contractual agreements, Büro Wassmann holds exclusive application rights in several European countries.

3 Project Progress and Deviations

Project start and framework conditions. The joint project *Schäfersee-Verfahren*® commenced with the start of funding on May 1, 2021. The objective was the further development and scientific validation of an environmentally compatible method for redox stabilization of urban water bodies through controlled addition of calcium nitrate and oxygen. Project management and technical development were led by Büro Wassmann, while the Technical University of Berlin, Chair of Environmental Microbiology, conducted microbiological and molecular biological analyses as well as joint field investigations. The originally planned project start was slightly delayed due to the late funding approval and pandemic-related conditions. In addition, an IT security incident at TU Berlin temporarily restricted data processing. Nevertheless, all planned work packages were initiated within the intended timeframe.

Year 2021 – Setup phase and initial investigations. In the first project year, the research initiative moved into operational implementation as scheduled. The focus was on establishing measurement methodology, conducting the first field investigations, and collecting reference data for subsequent system development. The work was carried out jointly by Büro Wassmann and TU Berlin, Chair of Environmental Microbiology.

- Installation and commissioning of a mobile pilot system for metered introduction of calcium nitrate at Schäfersee (Berlin-Reinickendorf);

- Initial water sampling and depth profiling to characterize the untreated baseline condition;
- Installation of additional online sensors (oxygen, redox, temperature, conductivity) at multiple depths on a floating pontoon;
- Setup of a web server for real-time data transmission and external monitoring of measurements;
- Start of regular dosing from late May 2021 as part of test operations;
- Joint collection and preparation of sediment cores by Büro Wassmann and TU Berlin for microbiological and geochemical analyses;
- Conduct of supplementary preliminary investigations at an industrial water body in Lower Saxony to evaluate different stress scenarios.

The work proceeded in accordance with the approved work plan. The surveys provided the methodological and data foundation for the subsequent development of the stationary system technology and the automated control strategy.

Year 2022 – Consolidation and methodological expansion. In the second project year, the investigations specified in the work plan were continued and methodologically expanded. The emphasis was on stabilizing ongoing operations at Schäfersee and preparing the development of the stationary installations.

- Continuation of physico-chemical measurement series at Schäfersee with sensors at different water depths and continuous online acquisition via the established web server;
- Regular sampling to capture seasonal variations in oxygen, redox potential, and nutrient distribution;
- Standardization of sample processing and data transfer between both partners;
- Planning and technical design of the stationary installation (implementation phase according to the project plan: March to June 2022);
- Installation of a measurement pontoon at the industrial water body in Lower Saxony (July 2022) with identical sensor setup and web server connection for continuous depth-profile acquisition;
- Coordination with specialist engineers and electricians to prepare the stationary system technology.

Manufacture and installation of the stationary system did not take place during this period, as design and control-technology details were first aligned. The results to date confirmed the suitability of the sensor suite and provided the data basis for later implementation of the automated control strategy. No substantive deviations from the approved work plan occurred.

Year 2023 – Site adjustment and start of extended investigations. In 2023, the project continued as planned, focusing on securing new sites and expanding the monitoring program. Following the completion of site selection, preparations for the runtime extension were initiated, and initial before–after investigations at the new Fennsee site commenced.

- Continuation of monitoring programs and dosing at Schäfersee with adapted sensor configuration and real-time data acquisition;
- Start of joint sampling at Fennsee by Büro Wassmann and TU Berlin to capture baseline conditions (before–after comparison);
- Expansion of investigations to include gas-trap measurements at Schäfersee and Fennsee to determine methane fluxes (each with 24 h integration time after sampling);
- Detailed site analyses and technical planning for the two new installations at Fennsee (Berlin) and Jörne Meerke (Neuss);
- Application for and approval of the project extension until April 2025 for implementation and trial operation of the new installations.

The investigations were carried out in close coordination between Büro Wassmann and TU Berlin and were consistent with the approved work plan. The results obtained formed the basis for the subsequent installation of the stationary systems and validation of the expanded methodology.

Year 2024 – Construction, commissioning, and extended investigations. During the 2024 extension period, the technical and scientific work continued and was completed as planned. The focus of the year was commissioning the two new stationary installations, integrating them into the existing monitoring network, and expanding the accompanying analyses.

- Construction and commissioning of a land-based system at Fennsee (Berlin) with online data acquisition, remote control, and dosing into the eastern basin (reference: western basin);
- Installation and commissioning of the system at Jörne Meerke (Neuss) with combined nitrate dosing and oxygen supply via mains water;
- Setup of a measurement pontoon at Jörne Meerke with sensors at various depths, connection to the web server, and remote transmission of all measurement data;
- Continuation of gas-trap measurements at Schäfersee and Fennsee to quantify methane fluxes (each with 24 h integration time after sampling);
- Execution of additional specialized investigations:
 - HPLC analytics to determine microcystins at Fennsee,
 - Investigations of geochemical phosphorus binding at Schäfersee and Jörne Meerke,
 - supplementary sampling and analyses within the *lanaplan* project at Jörne Meerke.
- Integration of all new systems into the existing web-server-based monitoring concept with real-time transmission and remote control.

The monitoring programs were conducted at all sites according to the work plan and expanded to address site-specific questions. Scheduling delays arose solely from weather-related constraints and logistical coordination during the commissioning phase. Overall, 2024 proceeded as planned and marked the conclusion of technical trials of the Schäfersee-Verfahren® under different water-body conditions.

Deviations from the original work plan. The key deviations from the original proposal resulted from external factors and the necessary change of sites:

- pandemic-related delays in personnel availability and sampling (2021–2022),
- temporary IT outages at TU Berlin with restricted data processing (2021),
- early termination of the subproject at the industrial site (industrial water body in Lower Saxony) and the resulting change of site (2023),
- project extension for installation and testing of the new systems (2024–2025).

Despite these adjustments, all work packages were implemented in substance. The project extension enabled full technical realization of both installations and verification of the method's effectiveness under different water-body conditions.

4 Work Packages and Results

This chapter presents the work packages processed within the project and describes the results achieved. The structure follows the work packages defined in the funding proposal, with emphasis on the activities conducted by Büro Wassmann. These include, in particular, the technical development and installation of the systems, water-body monitoring, evaluation of measurement data, and coordination of the overall project. The scientific investigations of the project partners—especially TU Berlin (Environmental Microbiology)—as well as subcontracted mineralogical analyses are additionally considered insofar as they contribute to understanding the overall results.

4.1 WP 00 – Project Coordination and Organization

Büro Wassmann was responsible for overall coordination of the collaborative project. This included coordinating all technical and organizational steps with the project partner Technische Universität Berlin (Chair of Environmental Microbiology) and integrating subcontractors, for example for mineralogical and geochemical investigations.

Originally, an industrial application partner with a process-water system was planned as a demonstration site. The process technology and automated control were to be tested there at large operational scale. After an intensive preparatory phase with baseline investigations and advanced planning for a stationary installation, the collaboration was terminated by mutual agreement before on-site implementation. It was therefore necessary to secure alternative demonstration sites.

The **Schäfersee** in Berlin-Reinickendorf was made available from the outset by the State of Berlin, represented by the Senate Department for Mobility, Transport, Climate Protection and the Environment. An extensive data basis from previous investigations and applications was already available here. For the **Fennsee** in Berlin-Charlottenburg/Wilmersdorf, the responsible district office was secured as the water-body owner, and for the **Jröne Meerke** in Neuss, collaboration was established with the local Office for Environment and Urban Green. These entities did not act as active partners in the consortium, but provided the water bodies and accompanied on-site implementation.

During the project period, regular work meetings were held—depending on the situation, on site at the study water bodies, at the institutes, or, due to the COVID-19 pandemic, online.

They served to coordinate progress, discuss methodological issues, and adapt to changed framework conditions following the loss of the originally planned industrial water body. A key component of coordination was also the alignment with the competent water authorities, particularly concerning permits for the application of calcium nitrate.

In addition, Büro Wassmann prepared interim reports, change requests (e.g., expansion to Fennsee and Jröne Meerke), and the final documentation for the BMBF. External communication also formed part of this work package: Büro Wassmann acted as the contact for the specialist public and media, prepared

information materials for a broader audience, and organized on-site appointments to demonstrate the systems.

In this way, it was ensured that the project could be successfully implemented despite content-related adjustments, and that both the scientific and practical objectives were fully achieved.

4.2 WP 01 – Microbiological Analyses (Technische Universität Berlin)

Microbiological investigations were conducted within the project by the Environmental Microbiology division at Technische Universität Berlin. The aim was to better understand the microbial processes in sediment and water column triggered by the Schäfersee-Verfahren® and to capture the effects of oxygen and nitrate application on microbial community structure.

For this purpose, sediment and pore-water samples were taken at the sites Schäfersee, Fennsee, and to a lesser extent Jörne Meerke. The focus of analyses was on Schäfersee and Fennsee, where complete treatment cycles were available.

The investigations comprised DNA-based analyses (16S rRNA sequencing, metagenomics, PCR and qPCR) as well as physico-chemical measurements of pore, deep, and surface water parameters (oxygen, nitrate, ammonium, phosphate, sulfate, dissolved iron, other (semi)metals, as well as organic pollutants, and methane and nitrous oxide in deep water). These data served to describe the respective redox environments and enabled inference of the underlying microbial metabolic processes.

The core processes examined were denitrification, sulfate reduction, and methanogenesis. The data allow an assessment of the extent to which the addition of nitrate and oxygen influences these functional groups and thereby contributes to stabilizing the sediment–water interface.

The data indicate that a microbial population already adapted to the Schäfersee-Verfahren was present in Schäfersee, consistent with the long-running restoration over several years. In Fennsee, by contrast, clear changes were detected at the level of 16S rRNA gene sequences as well as functional genes in response to the method compared with populations in sediment not supported by the Schäfersee-Verfahren. This shows that the Schäfersee-Verfahren stimulates biological processes that contribute to the oxidation of sulfidic compounds, iron and ammonium, as well as organic compounds, while initiating denitrification processes.

Detection of specific organism groups focused on potentially toxin-producing cyanobacteria. Although these were detectable in lake sediments via 16S rRNA gene analysis, no indications of risks due to the Schäfersee-Verfahren were identified. This was supported by molecular, analytical, and microscopic analyses.

4.3 WP 02 – Schäfersee (Berlin) – stratified water body, pontoon prototype

Schäfersee in Berlin-Reinickendorf served as the central reference water body and starting point for development and testing of the Schäfersee-Verfahren®. The approximately 4.5 ha stratified water body, with a maximum depth of about 7 m, has long been impacted by stormwater discharges from a highly sealed catchment exceeding 240 ha. As a result of high inputs of organic substances, anoxic conditions have occurred regularly in the deep water at least since the 1980s—probably much earlier—along with the formation of substantial sludge layers with intensive hydrogen sulfide and methane production.

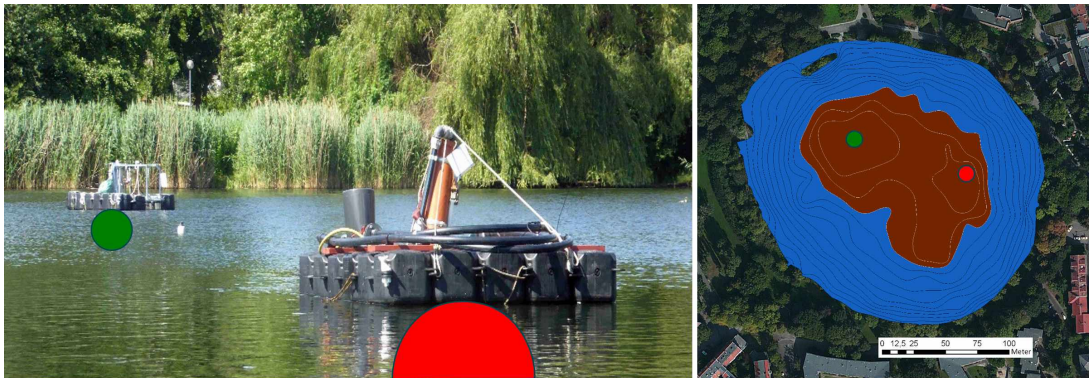


Figure 1: Schäfersee: Prototype floating installation with pontoons (left) and depth map with positions of the deployed pontoons (right). Green marks the pump pontoon, red the dosing pontoon. The brown-colored area (depth > 5 m) corresponds to the section treated by the method.

Since 2017, the lake has been regularly treated with the Schäfersee-Verfahren® on behalf of the Senate Department for Mobility, Transport, Climate Protection and the Environment of Berlin. A provisional pontoon solution was used that enabled targeted dosing of calcium nitrate in combination with oxygen-saturated water. The installation consists of a pumping pontoon and a dosing pontoon, connected by flexible lines. Water is drawn from the deep zone, enriched with oxygen, dosed with calcium nitrate, and then returned specifically to the anoxic layers below about 5 m depth. The depth map (Fig.1) shows the positions of the two pontoons; the blue area marks the water column down to about 5 m depth, and the brown zone beneath indicates the treated, formerly permanently anoxic area.

The installation is deployed several times a year for dosing phases of about two weeks. During these periods, calcium nitrate is introduced continuously in a controlled manner, with dosing adjusted to the measured oxygen and redox conditions. Treatment focuses exclusively on the hypolimnion in order to target the reductive processes occurring there without disturbing the lake's natural stratification.

Extensive measurements accompanied the treatment phases. These included continuous recordings of oxygen, redox potential, temperature, nitrate, and ammonium at various depths, supplemented by discrete water and sediment samples. This data basis made it possible to record the development of the redox environment and the effectiveness of nitrate application in detail.

With the start of the BMBF project, Schäfersee was integrated into a systematic research design to deepen the existing practical experience scientifically. Key focuses included quantifying effects on hydrogen

sulfide formation, methane release, phosphorus remobilization, and redox stabilization. Results from these measurements formed an important basis for designing the stationary systems later developed at other sites.

Originally, a permanent stationary installation at Schäfersee was also planned. This could not be implemented within the project period for organizational and administrative reasons but remains in planning. The goal is to operate dosing in the future in an automated, remote-controlled manner from a shore station. The insights gained from pontoon operation flowed directly into this technical advancement and confirmed the fundamental effectiveness of the method for long-term stabilization of deeply stratified, urban-impacted water bodies.

4.4 WP 03 – Development of compact stationary systems

A central project goal was the development and testing of compact, stationary systems for automated implementation of the Schäfersee-Verfahren®. These were intended to replace the provisional pontoon prototype previously used at Schäfersee and enable continuous, low-maintenance, remote-controlled dosing. Conceptual development was carried out by Büro Wassmann and implemented in practice at various sites.

Original planning at the industrial water body (Lower Saxony) The original proposal envisaged constructing the first stationary demonstration installation at an industrial water body in Lower Saxony. The system consists of several artificially constructed, interconnected basins forming part of an on-site process-water circuit. Water passes through several treatment stages before being fed back into technical processes. Due to long-term use and material loads, the basins exhibit marked accumulation of organic and inorganic material in the sediment. In particular, the originally intended main basin was characterized by anoxic deep-water conditions and pronounced reducing zones. Within the project, the aim was to demonstrate the effect of the Schäfersee-Verfahren® on an industrially influenced, stratified water-body system.

In 2021, Büro Wassmann conducted extensive baseline investigations. These included depth profiles of oxygen, redox potential, conductivity, and temperature as well as water analyses. Sediment samples were collected in cooperation with Technische Universität Berlin, which carried out microbiological and geochemical investigations. The results showed clear indications of high internal sediment loads with organic and metallic compounds typical of industrial recirculation systems.

On this basis, a detailed concept was developed for integrating a stationary system into basin P4, intended for targeted nitrate addition and oxygen enrichment. Site selection, technical planning, and hydraulic integration were carried out in close coordination with the industrial partner's environmental department. Before implementation could proceed, however, the cooperation was terminated by mutual agreement

for organizational and contractual reasons. The experience and technical insights gained during this planning phase directly informed subsequent developments at the Fennsee and Jröne Meerke sites.

Advancement of the system concept After the industrial water body could no longer serve as a demonstration site, development of the stationary systems was continued during the project and implemented at two different urban water-body types: the shallow stormwater retention basin **Fennsee (Berlin)** and the stratified excavation lake **Jröne Meerke (Neuss)**. Both sites offered ideal conditions to test the technical flexibility and transferability of the method under different morphological and chemical settings.

The central objective was to develop compact, modular technology that

- enables automated and remote-controlled dosing of calcium nitrate,
- ensures targeted and energy-efficient oxygen supply,
- adapts discharge specifically to depth and stratification conditions,
- minimizes maintenance effort and allows continuous data acquisition.

Fennsee (Berlin) At Fennsee, a fully stationary installation was constructed for the first time. It consists of a shore-based technical container with storage tank, control unit, and dosing equipment. Via underground pipelines, the calcium nitrate solution is conveyed to several turbojets positioned in the water body that distribute oxygen-enriched water evenly throughout the water column.

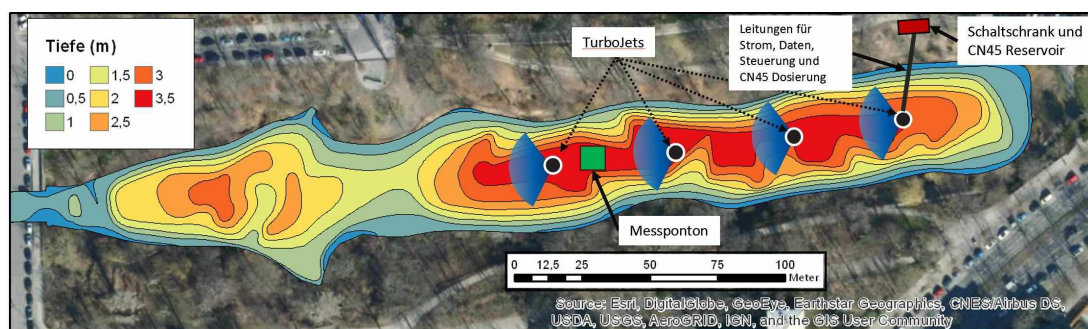


Figure 2: Fennsee: Overview map with depth information, positions of the turbojets, the container, the supply line, and the measurement pontoon.

Dosing is automated and can be controlled on demand via an online interface. A measurement pontoon with probes at different depths continuously transmits data on oxygen, redox potential, nitrate, and ammonium, enabling precise adjustment of dosing intervals. The system thus responds flexibly to short-term load peaks, especially after heavy rainfall events that are common in urban catchments.



Figure 3: Fennsee: View of the water body (left). Control and storage container with dosing equipment (right).

Jröne Meerke (Neuss) Jröne Meerke represents the second stationary application, with technical implementation specifically adapted to a stratified system. A particular feature is the use of the municipal drinking-water network as the oxygen source in combination with a separate dosing line for calcium nitrate. Both components are conveyed via independent lines to a pipe pump installed in the lake. The flow generated by the pump produces intensive mixing of the two streams and distributes the resulting oxygen- and nitrate-enriched water specifically in the deep zone below about 5–6 m. In this way, the reducing layer in the hypolimnion is supplied with electron acceptors without disturbing or overturning the lake’s natural stratification. The system is operated from a shore-based technical room with control and storage units and is fully automated and remotely controlled.

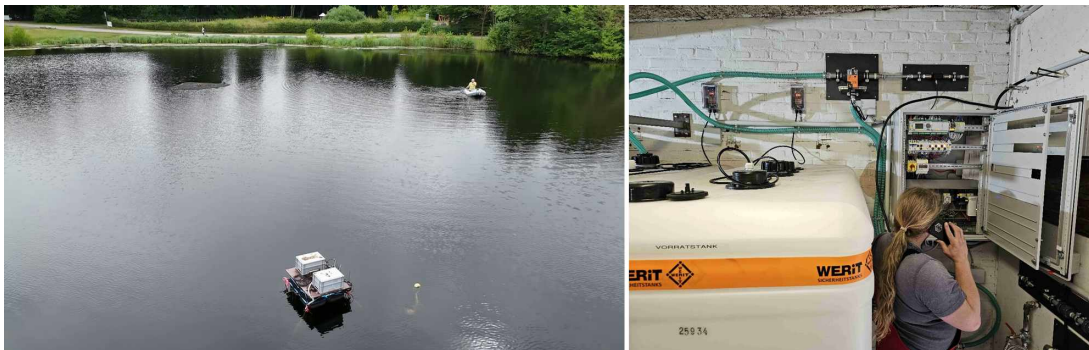


Figure 4: Jröne Meerke: View of the water body with measurement pontoon (left). Technical room with control and storage unit (right).

Here, too, a measurement pontoon with multi-level sensors was installed to monitor treatment effectiveness in real time. The measurement results showed that redox stabilization and phosphorus retention can also be reliably achieved in stratified systems when dosing is precisely controlled.

Conclusion With the systems developed at Fennsee and Jröne Meerke, the technical advancement targeted in the project was successfully implemented. The systems enable long-term, remote-controlled, and energy-efficient application of the Schäfersee-Verfahren®. At Schäfersee itself, construction of a comparable stationary installation remains in planning; the insights gained there form the basis for the next stage of implementation.

4.5 WP 4a – Industrial Water Body (preparation, not realized)

In the original project concept, the Schäfersee-Verfahren® was to be demonstrated at an industrial recirculation water body in Lower Saxony. To this end, Büro Wassmann carried out extensive preliminary investigations and planning in 2021, on the basis of which a detailed concept was developed for constructing a stationary installation within the site's process-water system. Due to organizational and regulatory framework conditions, technical implementation could not be realized. The insights gained during planning and concept development fed directly into the subsequent implementations at Fennsee and Jörne Meerke.

4.6 WP 4b – Fennsee (stationary application, shallow water body)

Fennsee in Berlin-Charlottenburg/Wilmersdorf is a typical urban shallow water body that is particularly burdened by stormwater inflows from a large catchment. The water body consists of two interconnected sub-basins—a western and an eastern basin—that exhibit similar morphological and chemical characteristics. Within the project, only the approximately 300 m long and 50 m wide eastern basin was treated, while the western basin served as an unaffected reference area.

Before measures began (2023), pronounced signs of stress were evident in the eastern basin: High loads of organic substances from stormwater regularly led to oxygen depletion, low redox potentials, increased ammonium formation, and noticeable odor nuisance due to hydrogen sulfide. Conditions in the untreated western basin remained a vivid reference example of typical processes in such urban retention basins during the project period.

After completion of preliminary investigations, a permanently installed stationary system was constructed in winter 2023/2024. It comprises a shore container with storage tank, control unit, and underground pipelines leading to several turbojets anchored in the water body. These generate uniform hydraulic mixing and enable targeted distribution of calcium nitrate and oxygen throughout the water column. The system was commissioned in April 2024 and operated throughout the year.

The dosing principle at Fennsee is based on event-driven pulse dosing carried out on demand in short intervals. Sensors record parameters such as oxygen, nitrate, ammonium, and redox potential in real time. Responses to dosing typically occur within minutes to a few hours: Nitrate distributes homogeneously within the water column within one to two hours and reaches the intended target concentrations. Targeted follow-up dosing can maintain nitrate content in the sediment at stable levels to reliably suppress reductive processes there.

In the 2024 project year, more than 40 individual dosing cycles were carried out, triggered semi-automatically via the control system. Depending on the need, dosing volumes ranged between 50 and 200 liters per event. This adaptive approach enabled continuous control of system responses and demonstrates the potential to regulate dosing fully automatically via control algorithms in the future.

The results show that the method can also be successfully applied in shallow, heavily burdened urban waters. While the treated eastern basin remained odor-free, exhibited stable redox conditions, and showed markedly reduced ammonium and phosphorus concentrations, the untreated western basin continued to display typical reductive processes. The concept was thus demonstrated successfully for polymictic shallow water bodies for the first time.

4.7 WP 4c – Jröne Meerke (stationary application, hypolimnion)

Jröne Meerke in Neuss is a former excavation lake that is predominantly shallow but features a central depression with depths up to eight meters. Prior to the project, this zone was regularly characterized by strong oxygen depletion, high reduction intensity, and hydrogen sulfide formation. The volume of the affected deep water amounts to only a few thousand cubic meters but possesses an exceptionally high potential for internal remobilization. During autumn turnover, this regularly led—despite the small volume—to substantial phosphorus and nutrient loads entering the entire water column. Jröne Meerke has no natural inflow or outflow; all inputs occur via atmospheric deposition and via waterfowl, especially a large goose population that has permanently established itself on the island located in the lake. The continuous nutrient input via goose droppings, together with internal remobilization processes, resulted in pronounced eutrophication and recurrent algal and cyanobacterial blooms. The water body thus represents a typical example of urban over-enrichment *without* nutrient-rich wastewater inflow.

The aim of this work package was to demonstrate the Schäfersee-Verfahren® in a stratified water body with a heavily burdened hypolimnion and to develop an effective, finely controllable treatment concept. To this end, a stationary system connected to the drinking-water network was constructed in spring 2024. Drinking water serves as the oxygen source and is conveyed via a dedicated line to a pipe pump, while calcium nitrate is dosed via a second line. In the pipe pump, the two components are intensively mixed before the nitrate- and oxygen-enriched solution is introduced directly into the hypolimnion at about 5–6 m depth. Control and monitoring of the system are carried out via a shore-based technical station with automatic data acquisition and remote access.

Extensive preliminary investigations were conducted as early as 2023, including depth profiles of oxygen, redox potential, nitrate, ammonium, and temperature, as well as water sampling for chemical analysis. The monitoring system was supplemented by a central pontoon that measures continuously at multiple depths: oxygen probes at 1, 3, 6, and 7.5 m depth, nitrate probes at 1, 6, and 7.5 m, and redox sensors in the deep zone at 7.5 m. All installed probes simultaneously record water temperature, enabling precise tracking of the lake's thermal stratification behavior. This made it possible to document the course and intensity of summer stagnation as well as the timing and duration of autumn turnover continuously.

Actual dosing began in mid-April 2024. At the start of the measure, an initial pulse dosing with elevated nitrate concentration was carried out due to the high consumption rates, in order to neutralize the strong reducing capacity of the sediment. Within a few days, a marked increase in redox potential and

complete suppression of hydrogen sulfide formation were observed. Subsequently, a finely tuned control concept was developed in which minimal doses of about 10 liters were applied daily or every other day. This micro-cyclical dosing strategy enabled very uniform, stable nitrate supply to the hypolimnion and led to persistently positive redox conditions without affecting stratification.

Targeted sediment investigations complemented the water measurements. For this purpose, Büro Wassmann collected stratified samples from sediment cores in summer 2024, which were separated centimeter-wise, frozen, and subsequently handed over to Technische Universität Berlin. In parallel, the **lanaplan** office (NRW) conducted supplementary investigations on phosphorus remobilization and binding forms. It became evident that the sediment functioned as a pronounced phosphorus source before the measure, whereas after nitrate treatment it showed a significant shift to phosphorus sink behavior. These changes confirm successful stabilization of redox conditions and the establishment of durable mineral binding forms.

Overall, the measure led to sustained stabilization of deep water and a clear ecological improvement. In the formerly inhospitable deep zone, zooplankton and even dragonfly larvae were again detected at depths of six meters—a clear indication of recolonization of the previously anoxic zone. This demonstrated that the Schäfersee-Verfahren® can be successfully applied even under altered technical boundary conditions. Adapting the application technology—the use of drinking water as an oxygen carrier in combination with targeted introduction via a pipe pump—proved as effective as the classic aeration variant with pontoons. In this way, it was shown that the method can be flexibly adapted to different water-body types and technical boundary conditions without loss of effectiveness. Treatment of Iröne Meerke thus confirms transferability of the concept to smaller, stratified lakes with locally confined, strongly reducing deep zones.

4.8 WP 05 – Public Outreach and Transfer

In addition to technical and scientific development, a key project goal was targeted communication of results and the promotion of knowledge transfer to practice and the public. Büro Wassmann assumed both substantive and organizational responsibility for these activities.

At the start of the project, the initiative received media coverage by the Federal Ministry of Education and Research (BMBF). In coordination with the project team, the BMBF's communications unit produced a short video that was published on various social media channels (Instagram, TikTok, YouTube) and vividly presents the core idea of the Schäfersee-Verfahren® and the objectives of the collaborative project. In parallel, an extensive documentary film about the project was produced in cooperation with a professional media agency. This film documents development and implementation at the Schäfersee, Fennsee, and Iröne Meerke sites, includes interviews with experts and project participants, and illustrates the method's significance for sustainable water protection. The video material was prepared for both professional events and general public outreach.

Another milestone in media presence was a feature by *Deutsche Welle*, which produced a roughly ten-minute film about the project and broadcast it internationally. This feature reached a worldwide audience and contributed significantly to making the method known in an international context.

In addition, several specialist talks and scientific presentations were given at national and international conferences where project results were presented and discussed:

- *2nd International Congress on Microbial Ecotoxicology (EcotoxicoMic 2021, Montpellier, France)* – Poster: *Impact of a nitrate-dependent remediation procedure on sediment pollutants in a contaminated urban lake.*
- *36th Congress of the International Society of Limnology (SIL 100, Berlin, Germany / online, 07.–10. 08. 2022)* – Poster: *Influence of the addition of calcium nitrate and oxygen enriched water on the hypolimnion of a contaminated urban lake.*
- *2nd International Conference on Urban Water Interfaces (UWI 24, Berlin, Germany, 22.–24. 04. 2024)* – Poster: *Benefits and risks of a calcium nitrate and oxygen-dependent treatment method for contaminated urban lakes.*
- *39th DGL Annual Conference 2024 (Dresden, Germany, 16.–22. 09. 2024)* – Poster: *A nitrate and oxygen-based treatment strategy to improve water quality in contaminated urban lakes.*
- *ASLO 2025 Aquatic Sciences Meeting (Charlotte, NC, USA, 26.–31. 03. 2025)* – Talk: *Treatment with nitrate and oxygen improves water quality of contaminated urban lakes.*

Moreover, the Schäfersee-Verfahren® was presented to a broad professional audience in an online seminar of the *Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau (BWK)*. Further presentations and discussions with authorities, engineering firms, and municipal representatives supported dissemination and debate of the method.

Project success led to a number of practical follow-up applications and cooperation requests. These include the water bodies *Kahnteich* and *Judenteiche* in Goslar (UNESCO World Heritage Site Rammelsberg), *Waldsee Hermsdorf* in Berlin, as well as a water body in Panketal, where the method is successfully used to stabilize odors and remobilization. Short-term applications for acute stabilization were also tested in Berlin.

For further dissemination, a dedicated website was set up specifically for the BMBF project. This project page presents the goals, progress, and results of the research initiative and offers illustrative insights into the application of the Schäfersee-Verfahren® at the various demonstration water bodies. A link with the main page of Büro Wassmann is planned to further facilitate access for the specialist public and interested municipalities.

In the international context, initial contacts were established for potential applications abroad. Among other things, a joint project proposal was submitted for combined application at the heavily eutrophied *Lough Neagh* in Northern Ireland, the largest lake in the United Kingdom. In addition, concepts are currently being developed to adapt the method for use in reservoir systems, where problems with hydro-

gen sulfide and redox instabilities are increasingly occurring—particularly in drinking-water reservoirs in which classic aeration systems reach their limits.

Thus, Work Package 5 made a decisive contribution to disseminating the project results beyond the immediate research context, fostering acceptance among authorities and the specialist public, and preparing transfer to practical application fields nationally and internationally.

5 Additional Investigations

In the course of the project, new research questions arose based on ongoing observations and measurements that went beyond the originally planned work packages. These were addressed as additional investigations, which were integrated into the research program in the final project year.

The triggers were, in particular, the changes in nutrient ratios observed during application of the Schäfersee-Verfahren®. It was demonstrably found that phosphorus concentrations in the water decreased significantly more in several water bodies than initially expected. This raised questions about the processes leading to phosphorus binding in the sediment, as well as possible geochemical changes in the redox system.

In parallel, a study appeared in the scientific literature suggesting potential links between nitrate addition and the formation of certain cyanotoxins. The results indicate that altered nitrogen–phosphorus ratios could influence the occurrence of cyanobacteria and their microcystin production. To clearly assess this issue in the context of the Schäfersee-Verfahren®, supplementary investigations into cyanobacteria and cyanotoxins were incorporated into the work program.

The additional investigations therefore focused on four areas:

- geochemical and mineralogical analyses of sediments (TU Berlin),
- quantitative investigations of phosphorus binding and sediment stability (lanaplan GbR, Nettetal),
- establishment and application of an HPLC method for identification and quantification of microcystins as well as microbiological analyses of cyanobacterial populations (TU Berlin, Environmental Microbiology),
- groundwater investigations at Schäfersee to detect possible nitrate migration and to verify any influence of the method on the surrounding groundwater (TU Berlin, Environmental Microbiology).

Groundwater samples were collected at several monitoring wells in the shore zone of Schäfersee and analyzed chemically. In none of the wells investigated were elevated nitrate concentrations or indications of an influence from the application of the Schäfersee-Verfahren® detected. The results thus support the assumption that process control remains within the surface water and that no relevant vertical nutrient transfer into groundwater occurs.

The results of these activities are summarized in the following sections and serve to deepen the scientific understanding of the effects achieved with the Schäfersee-Verfahren®.

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5.1 Sediment Analyses Jöne Meerke (lanaplan GbR, 2025)

To provide a complementary assessment of the effect of the Schäfersee-Verfahren® in the water body Jöne Meerke, detailed sediment investigations were carried out by Lanaplan GbR (Nettetal) on behalf of Büro Wassmann. The aim was the experimental determination of phosphorus release rates as well as analysis of phosphorus binding forms in the sediment. The work took place from February to October 2024, i.e., during the introduction and operational phase of calcium nitrate dosing.

Methodological Approach Sampling was conducted at a fixed site at 8.7 m water depth. On six dates, intact sediment cores were taken and examined under defined laboratory conditions. Phosphorus release rates were determined in 48-hour incubation experiments under anoxic conditions in the dark to simulate maximum phosphorus release from the sediment. In parallel, oxygen concentrations immediately above the sediment were measured in situ.

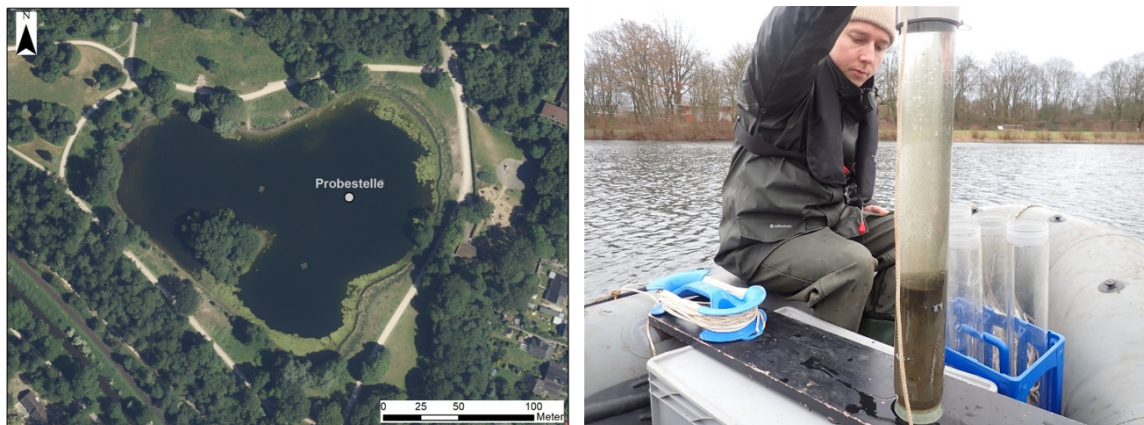


Figure 5: Jöne Meerke: Left, aerial image with marked sampling location; right, extraction of a sediment core during sampling (lanaplan GbR, 2024).

To determine phosphorus binding forms, the established sequential extraction procedure according to Psenner *et al.*, 1988 with modifications after Hupfer *et al.*, 1995; Hupfer and Lewandowski, 2008 was applied. This enabled differentiation of the fractions “labile P”, “reductively soluble P”, “metal-oxide-bound P”, “organic P”, “acid-soluble P” and “refractory P” and allowed estimation of the sum of mobilizable phosphorus fractions. Analyses were performed by an accredited laboratory (SEWA GmbH, Essen).

Results Before the start of calcium nitrate dosing (February to May 2024), experimentally determined phosphorus release rates ranged between $0.005 \text{ g m}^{-2} \text{ d}^{-1}$ and $0.009 \text{ g m}^{-2} \text{ d}^{-1}$. In this phase, the sediment acted as a phosphorus source, i.e., there was a slight net flux from the sediment into the water column.

After the start of calcium nitrate application at the end of May 2024, consistently negative release rates were recorded (June–September 2024: -0.007 – $-0.019 \text{ g m}^{-2} \text{ d}^{-1}$), documenting a reversal of flux direction: phosphorus was removed from the water column and bound in the sediment. In October 2024,

the release rate was $0.002 \text{ g m}^{-2} \text{ d}^{-1}$, which is to be classified as practically no release (Nürnberg, 1984; Sondergaard *et al.*, 2003). Thus, the management target value recommended in the literature of less than $0.01 \text{ g m}^{-2} \text{ d}^{-1}$ was consistently met.

Total phosphorus content of the sediment ranged between 1.4 gP/kg and 2.1 gP/kg, and is therefore considered high. The dominant fraction was organically bound phosphorus, followed by acid-soluble P (carbonate-bound) and refractory P. The proportion of potentially mobilizable phosphorus (sum of labile, reductively soluble, and organically bound fractions) ranged between 38 % – 64 % of total phosphorus, with a maximum in July 2024 (approx. 1.3 gP/kg). After the start of nitrate dosing, a temporary increase in the reductively soluble and metal-oxide-bound phosphorus fractions was observed in June 2024. However, this change was only transient and was no longer apparent during the subsequent investigation period. No significant or persistent trends in the individual fractions were identified.

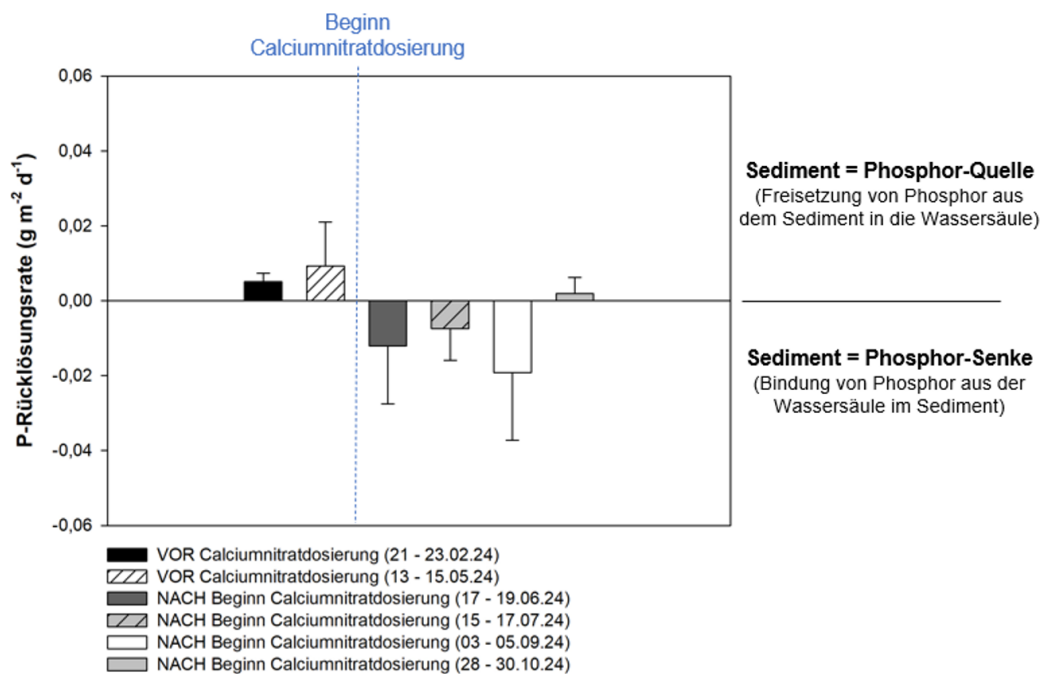


Figure 6: Jöne Meerke: change in phosphorus release rates before and after the start of calcium nitrate dosing. Negative values indicate binding of phosphorus in the sediment (phosphorus sink).

Assessment The investigations demonstrate that the treatment applied at Jöne Meerke according to the Schäfersee-Verfahren® brought about a clear reversal of phosphorus dynamics. A sediment that functioned as a net source of phosphorus prior to the measure became a stable phosphorus sink within a few weeks. Release rates fell below the relevance threshold and remained negative over several months, indicating sustained binding of phosphorus in the sediment. The results highlight the effectiveness of the method: the combined, targeted addition of calcium nitrate and oxygen stabilized the redox environment in the hypolimnion and prevented remobilization of phosphorus from the sediment. Thus, a sustainable improvement in water quality was demonstrably achieved at Jöne Meerke.

5.2 Geochemical–Mineralogical Investigations (TU Berlin, 2024)

Objective and Approach The geochemical–mineralogical accompanying investigations were conducted by the Chair of Applied Geochemistry at Technische Universität Berlin within the project. The aim was to better understand the processes of phosphorus removal during application of the Schäfersee-Verfahren® and to examine whether addition of calcium nitrate leads to mineral binding of phosphate in the sediment. For this purpose, both the distribution and concentration of phosphorus in the sediment and the mineral phases in which phosphorus occurs were to be investigated. In parallel, the form of this binding in different water body types—Schäfersee (Berlin) and Iröne Meerke (NRW)—was examined.

Sampling and Analytics At Schäfersee, sampling took place before and after calcium nitrate application using a Mondsee corer in the immediate vicinity of the discharge site. Intact sediment cores with a length of about 25 cm and preserved sediment surface could be obtained. Part of the samples was processed in 1 cm layers for chemical and mineralogical analyses; another part was halved while frozen, freeze-dried, and embedded in resin to display spatially resolved element distributions using micro X-ray fluorescence analysis (μ XRF). Analyses were performed in the MAGMA laboratory of TU Berlin by X-ray fluorescence analysis (XRF), X-ray diffractometry (XRD), and μ XRF. At Iröne Meerke, comparable sediment cores before and after the first calcium nitrate application were available; here, due to logistical conditions, only 1 cm layers were processed.

Results Schäfersee Geochemical analyses show no significant differences in the major-element composition of the sediments before and after calcium nitrate addition. The mean phosphorus content is about 1 wt% P_2O_5 . In the upper 12 cm of the sediment, a clear enrichment of phosphorus is evident.

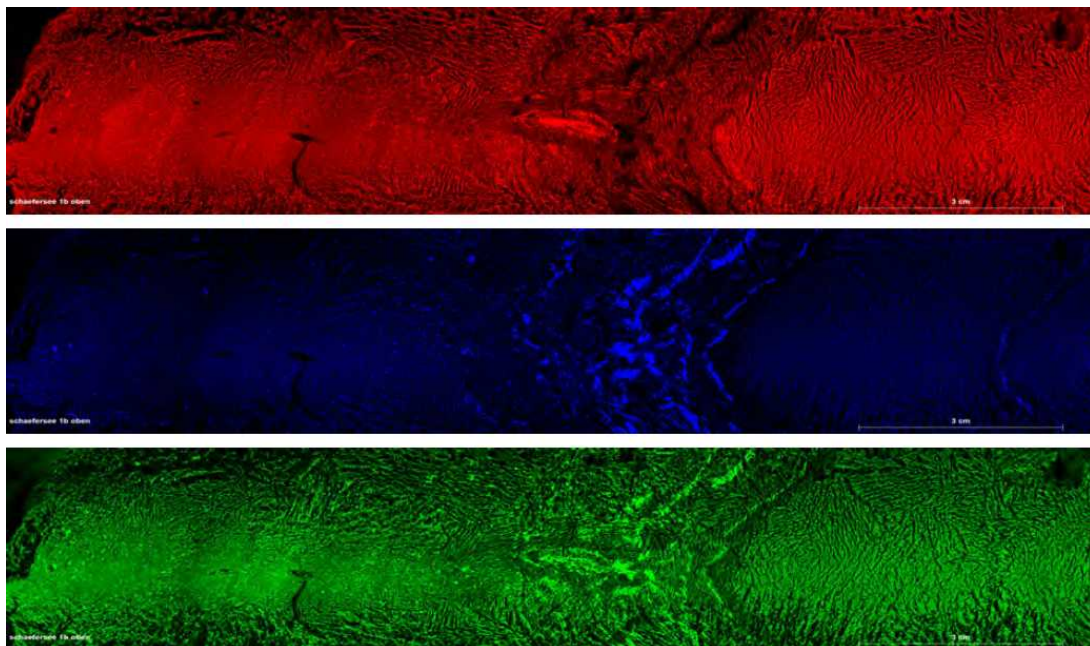


Figure 7: Schäfersee: μ XRF element distribution with phosphorus (green) at Fe-rich aggregates (red); Ca-rich laminations occur in deeper layers.

These iron–phosphorus aggregates occur predominantly in the upper part of the sediment cores, while calcium-rich layers are more common in deeper sections. In the X-ray diffractograms, the principal mineral phases quartz, mica, clay minerals, calcite, and pyrite were identified. In addition, the iron(II) phosphate mineral vivianite was unequivocally detected—and exclusively in the upper approximately 15 cm of the sediment column. Below this zone, binding of phosphorus to calcite dominates. Other phosphate minerals such as apatite were not detected. The μ XRF analyses show that phosphorus is associated both with calcium in fine calcite laminations and with iron in small-scale aggregates. The results suggest that phosphate near the sediment surface is bound in the form of vivianite, whereas in deeper layers co-precipitation with calcite occurs. The penetration of the calcium nitrate solution into the near-surface sediment is considered crucial for this process, as it eliminates hydrogen sulfide and enables binding to Fe oxyhydroxides, which can subsequently transform into vivianite.

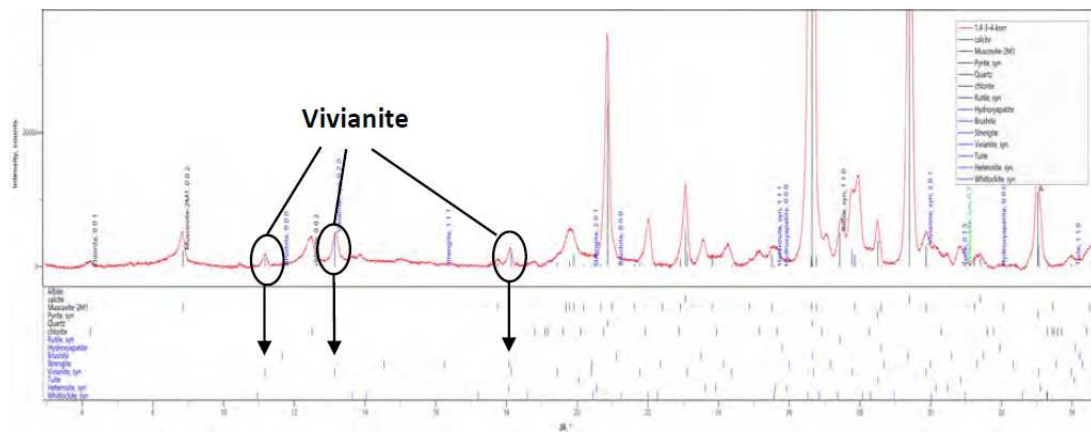


Figure 8: X-ray diffractogram Schäfersee: detection of the mineral phases chlorite, muscovite, quartz, calcite, pyrite, and vivianite in the upper 15 cm.

Results Järne Meerke Phosphorus contents in the sediment of Järne Meerke are overall lower than in Schäfersee (approx. 0.5 wt% P_2O_5). After the first calcium nitrate addition (core JM2), higher phosphorus contents were found than before the measure (core JM1), both in absolute terms and normalized to loss on ignition. This indicates additional binding of phosphorus in the sediment. In the XRD analyses, vivianite was not detected here, which is attributed to the significantly lower iron content of the sediments. As a possible phosphate mineral phase, brushite ($CaHPO_4 \cdot 2H_2O$) is mentioned, which occurred only in the treated core JM2, although it could not be identified unambiguously due to weak signals.

Assessment The investigations show that the Schäfersee-Verfahren® leads to removal of phosphate from the water column and that phosphorus is fixed in the sediment in different ways depending on lake type. In Schäfersee, phosphorus is bound near the sediment surface in the form of vivianite, whereas in Järne Meerke, due to lower iron availability, binding via calcium-bearing phases is more likely. Detection of vivianite in Schäfersee is considered indicative of mineral phosphate binding under sulfide-free conditions.

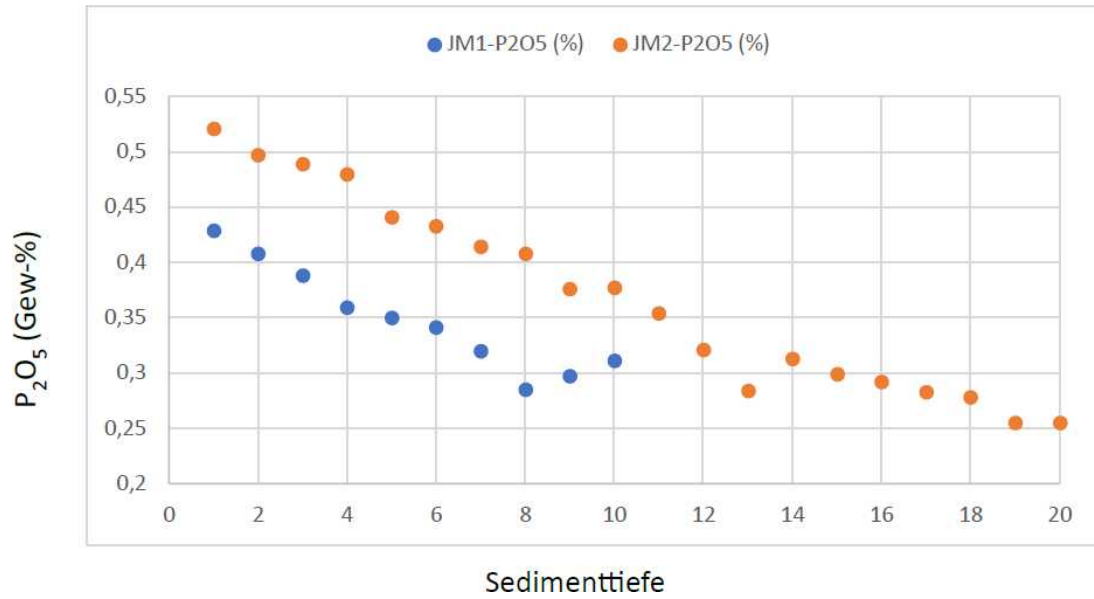


Figure 9: Phosphate concentrations in surface sediments of Jřone Meerke before (JM1) and after (JM2) the application with Ca-nitrate.

6 Scientific and Technical Results

This chapter summarizes the scientific and technical results of the overall project and describes the progress achieved regarding the mode of action, ecological evaluation, and technical implementation of the Schäfersee-Verfahren®. The presentation is based on the jointly collected measurement, analysis, and experimental data of Büro Wassmann and Technische Universität Berlin, Chair of Environmental Microbiology. For better comparability, the evaluation is parameter-based so that the observed relationships can be interpreted independently of site-specific conditions.

The focus is on redox stabilization, the suppression of reductive processes, phosphorus dynamics in the sediment, and accompanying microbiological changes. This describes the central mechanisms of action of the method and assesses their significance for stabilizing urban, organically burdened water bodies.

6.1 Necessity and Appropriateness of the Work Performed

The aim of the investigations carried out in the project was to test the mode of action and ecological compatibility of the Schäfersee-Verfahren® under real-world conditions. Since each water body has an individual load and contamination profile, a modular and site-specifically adapted research approach was required. Only the combination of field measurements, continuous monitoring, chemical analytics, and microbiological analyses made it possible to fully capture the complex redox processes and material cycles.

Cross-Lake Approach The selection of several water bodies—from the long-term treated Schäfersee to the newly treated Fennsee and the Jörne Meerke—was necessary to capture both short-term responses and long-term system development. Comparing different lake types allows assessment of the transferability of the method to other contaminated or eutrophic waters and provides robust indications of site-dependent differences in redox behavior.

Monitoring, Sensor Technology, and Water Analytics Continuous monitoring of physico-chemical parameters formed the central control instrument of the Schäfersee-Verfahren®. The method does not target a single chemical reaction in the sediment, but a controlled influence on redox conditions throughout the deep-water body. Therefore, the accompanying measurement and data management was not merely a supporting step but an integral component of the functional principle.

A stationary measurement pontoon housed a permanent sensor and data recording system that captured temperature, oxygen, redox potential, and conductivity in real time. These continuous data formed the basis for the dosing strategy of nitrate and oxygen application. Through close feedback between measured values and control, redox dynamics could be specifically influenced to suppress anaerobic processes (sulfate reduction, methanogenesis) and stabilize oxidative conditions.

In addition, regular water analyses from different depths (nitrate, ammonium, phosphate, sulfate, iron)

were conducted to validate chemical system development and mass balances. Monitoring thus provided both the empirical basis for scientific evaluation and the operational foundation for process control. This linkage of observation and control represents the unique feature of the Schäfersee-Verfahren® and the key methodological advance over classical lake restoration approaches.

Furthermore, an existing groundwater well at Schäfersee was incorporated into the study program to examine possible effects of nitrate dosing on adjacent groundwater. At no time did the analyses show elevated nitrate concentrations or other indications of groundwater influence. This confirms that nitrate application remains confined to surface water and does not cause vertical transfer of substances into the aquifer.

Sediment and Pollutant Analyses Sediment analyses served to understand the ongoing biogeochemical processes and potential risks. Particular attention was paid to metallic and organic pollutants. Iron was considered a key factor because it can, on the one hand, bind phosphorus and thus contribute to internal nutrient elimination and, on the other, act as an indicator of redox conditions in the sediment. It was also examined whether contaminated sediments might mobilize metals due to oxygen and nitrate application—a risk that, despite high heavy metal contents in the sediment, was not confirmed. Investigations of organic pollutants (PAHs, petroleum hydrocarbons, EOX) under real environmental conditions enabled a differentiated assessment of oxidative degradation and provided the first robust data on the long-term stability of the sediment matrix.

Microbiological and Molecular Investigations Microbiological analyses, conducted by the Environmental Microbiology group at Technische Universität Berlin, were necessary to understand the mechanisms of the observed redox shifts. They show how microbial communities respond to nitrate and oxygen supply, which functional groups are involved, and to what extent risks exist, for example due to toxigenic *Microcystis* populations. Results from qPCR, HPLC, and metagenomics analyses demonstrate that there was no indication of undesirable cyanobacterial developments and that nitrate application is associated with a clear increase in oxidative and denitrifying metabolic pathways. The functional genes identified (e.g., oxygenases) also indicate an increased potential for the degradation of organic pollutants under oxygen influence.

Overall Assessment The combined approach of continuous measurement, chemical-analytical control, and molecular biological characterization was necessary and appropriate to understand the functioning of the Schäfersee-Verfahren® holistically. It enables not only the evaluation of short-term effects but also statements on long-term stabilization and ecological safety. Thus, the project objectives were achieved and, at the same time, robust foundations were laid for applying the method in other burdened water systems.

6.2 Oxygen Budget and Redox Stabilization

The development of oxygen concentration and redox potential in the deep water of Schäfersee demonstrates the fundamental effect of the Schäfersee-Verfahren®. In 2015 and 2016, preliminary investigations were conducted without treatment. From July 2017 onward, continuous application of calcium nitrate in combination with oxygen-enriched water began. The system responded rapidly: the redox potential rose abruptly and has remained in the positive range since then, while oxygen in the deep zone became established in parallel (Figs. 11, 10).

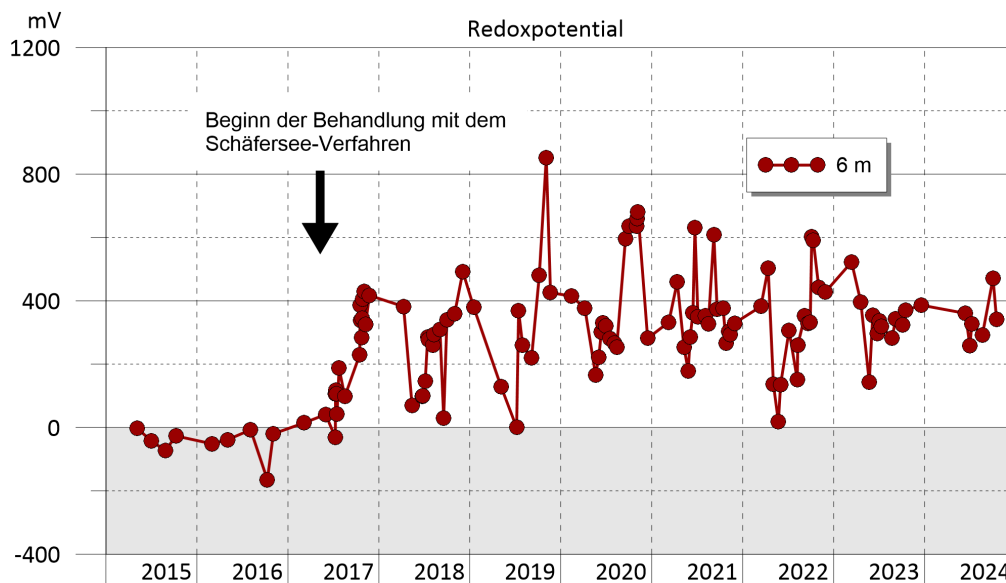


Figure 10: Redox potential at 6 m depth in Schäfersee, 2015–2024. Abrupt increase and permanent stabilization after the start of treatment.

Before 2017, redox values at 6 m depth were predominantly negative (below 0 mV), accompanied by anoxic conditions and typical hydrogen sulfide formation. After the start of treatment, the redox potential increased to between +300 and +800 mV and remained above the zero line even during summer stagnation phases. At the same time, measurable oxygen in the deep water could be detected for the first time. During the summer half-years, values peaked at 8 to 10 mg l⁻¹, whereas they had previously been near 0 mg l⁻¹.

This development evidences a permanent stabilization of the redox environment. The effect is particularly clear during autumn turnover: since 2018, oxygen from the upper water layers has regularly penetrated to 6 m depth and persisted there. This was not the case in the untreated phase. The data suggest that the deep water has since acted as a buffer zone that prevents the upward flux of oxygen-demanding substances from the sediment. Accordingly, oxygen conditions in surface-near layers also remain stable.

This behavior illustrates the central mode of action of the method: establishing a stable redox potential suppresses reductive processes in the sediment while oxygen demand in the water column decreases.

The system remains oxidizing for years without the need for physical full circulation.

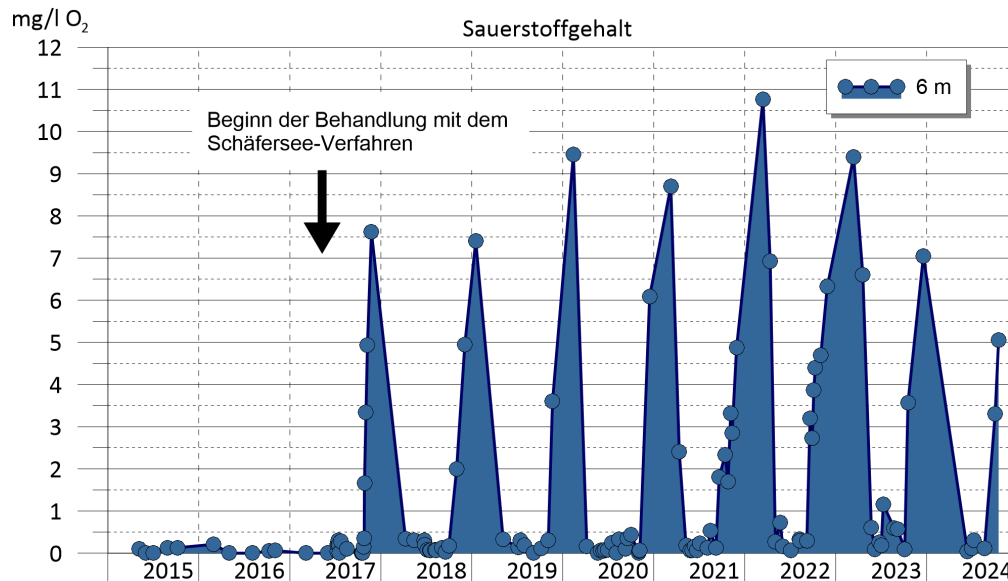


Figure 11: Oxygen concentration at 6 m depth in Schäfersee, 2015–2024. Start of treatment with the Schäfersee-Verfahren® from July 2017.

An analogous behavior was also observed at Jörne Meerke, where the redox potential in the hypolimnion rose markedly after initiation of treatment, thereby stopping phosphorus release (see Section 6.5). At Fennsee, surface-near pulse dosing stabilized the oxygen balance throughout the entire water column; deficits occurring after heavy rainfall events could be fully compensated by short-term daily re-dosings within a few days.

6.3 Oxygen Budget

Continuous measurements at the Schäfersee pontoon show that oxygen conditions remained stable over the entire investigation period without any significant impairment due to treatment with the Schäfersee-Verfahren®. From 2022 onward, after full installation of all probes, continuous data were available for three depth levels (1 m, 3 m, and 4,5 m). Concentrations fluctuated depending on stratification and weather conditions but remained consistently in the oxic range (6–12 mg l⁻¹) in the surface layer. In deeper measurement points, oxygen depletion occurred at times during summer stagnation phases, but without a relapse into a reducing milieu.

This observation highlights the mode of action of the method: targeted nitrate dosing stabilizes the redox system so that an oxidizing milieu is maintained even at low or absent oxygen availability. Nitrate availability buffers reducing potential, thereby suppressing reductive processes (e.g., sulfate reduction). In parallel, ammonium degradation is promoted and redox potential remains positive. The result is a stable, mildly oxidizing milieu that favors phosphorus binding in the sediment.

The probe measurements clearly reflect this relationship: during the spring months prior to dosing (April–May) the redox potential drops slightly and small amounts of ammonium can be detected. After dosing starts in June, redox potential and nitrate concentration increase noticeably while ammonium values decline. Oxygen shows no immediate correlation, confirming the decoupling between oxygen concentration and redox state via nitrate control.

Supplementary on-site measurements during the winter months also show that measurable oxygen reappears at 6 m depth in Schäfersee. This suggests that the redox stabilization achieved by nitrate application enables the return of oxidizing conditions even in deeper water layers. The measurement pontoon itself is not located in the area of maximum water depth (Z_{\max}), which is why the installed sensors capture this effect only partially.

A comparable pattern was also observed in Jörne Meerke, where treatment raised the redox potential in deep water and thus prevented phosphorus release (cf. Section 6.5). At Fennsee, treatment led to a general stabilization of the oxygen budget throughout the water column. The system responds particularly sensitively to weather events there; however, event-triggered pulse dosing fully compensated every short-term oxygen drop within a few days.

6.4 Inhibition of Reductive Processes and Gas Formation

Stabilization of redox potential through nitrate and oxygen led to a marked inhibition of reductive processes in all treated water bodies and thus to suppression of gas formation in the sediment. Under natural anoxic conditions, microorganisms use sulfate and carbon dioxide as alternative electron acceptors, leading to the formation of hydrogen sulfide (H_2S) and methane (CH_4). These substances are not only toxic but also cause substantial odor nuisances and, upon release to the atmosphere, contribute to the climate impact of eutrophic water bodies.

By supplying nitrate (NO_3^-) as a higher-ranked electron acceptor, this metabolic pathway was deliberately suppressed. Nitrate is preferred in the redox hierarchy, so sulfate reducers and methanogens are outcompeted energetically. As a result, treated sediment zones transitioned from reductive to oxidative metabolic conditions, which was clearly reflected in the measurement data and observed gas formation processes.

- H_2S : Odor emissions were completely eliminated in treated sections. At Fennsee, where foul odors had previously been regularly perceived in the surroundings, event-triggered dosing reliably suppressed H_2S peaks shortly after commissioning. At Schäfersee, only minimal amounts of dissolved hydrogen sulfide were detected over several years. These observations confirm that sulfate reduction in the upper sediment layers was entirely inhibited by nitrate supply.
- CH_4 : Methane production in the sediment as well as methane release via ebullition (bubble rise) and diffusive emission decreased significantly after application of the Schäfersee-Verfahren®. This was clearly evidenced by both sediment analyses and gas trap measurements. At Fennsee, a

pronounced decline in methanogenesis in the sediment and a markedly lower methane release via gas traps were measured. At Schäfersee, methanogenic activity also decreased, although a slight increase was occasionally observed in mid-summer; overall, the methane level remained well below baseline values. These results confirm the microbial competition mechanism between denitrification and methanogenesis and the sustained suppression of methanogenic processes. A quantitative assessment of avoided methane release is provided in the context of climate relevance (see Section 6.7).

- N_2O : Transient formation of nitrous oxide, a natural intermediate of denitrification, was detected in deep water immediately above the sediment layer at Schäfersee. At Fennsee, N_2O remained below the detection limit in the concentration range examined. The values measured at Schäfersee indicate a temporary intermediate formation that is subsequently reduced to molecular nitrogen (N_2) during complete denitrification. No indications of increased nitrous oxide release were found in this study. Given the high global warming potential of N_2O ($GWP_{100} \approx 265\text{--}298 \times CO_2$), this finding is particularly relevant, as it shows that no significant emissions occur despite transient formation. Further investigations should address quantitative budgeting of gases actually escaping from the water column as a function of nitrate dosing and redox state.

The inhibition of hydrogen sulfide, methane, and nitrous oxide formation had profound impacts on the entire ecological system. In the absence of toxic sulfur compounds, benthic habitats became recolonizable and oxygen demand in deep water declined significantly. The reduction in CH_4 and N_2O release additionally contributes to lowering climate-relevant emissions, since methane has roughly 30 times higher (GWP_{100}) (see Section 2.5). Thus, suppression of gas formation represents one of the central mechanisms of action of the Schäfersee-Verfahren®—both ecologically and in terms of climate policy.

6.5 Phosphorus Dynamics and Sediment Processes

The development of phosphorus concentrations in Schäfersee illustrates the lasting effect of the Schäfersee-Verfahren® on phosphorus availability in deep water. Only a few years after treatment began, total phosphorus (TP) values in deep water fell markedly. While concentrations of up to 2 mg l^{-1} still occurred in 2015 and 2016, values from 2021 onward were in the range of $0,05\text{--}0,2 \text{ mg l}^{-1}$ (Fig. 12).

The boxplot evaluation clearly highlights this difference: the median of total phosphorus concentrations decreased by more than one order of magnitude, and the range of measured values narrowed significantly. The system has shown no further release events and remains stable even in the summer months. This development evidences a shift from an internally driven phosphorus source to a stable phosphorus sink.

The observed stabilization is based on establishing a permanently oxidizing milieu at the sediment–water interface. Nitrate dosing maintains a redox level that suppresses the reduction of iron(III) and sulfate compounds. As a result, iron remains available in the oxidized state, and phosphate is preferentially

bound in poorly soluble iron phosphates. A direct determination of the binding form was not carried out here; however, complementary sediment-analytical investigations by Technische Universität Berlin indicate formation of vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) in near-surface sediment layers. These analyses were conducted by the Environmental Microbiology group and the Institute of Applied Geochemistry (Prof. Neumann). The detection of vivianite indicates a reduced iron(II) phosphate as a stability form that persists long-term at the sediment surface under mildly oxidizing conditions. Iron(III)-bound phosphorus likely coexists, although this has not yet been unequivocally confirmed analytically.

At Schäfersee, where the method has been applied continuously since 2017, a permanent shift in the sediment milieu has thus been achieved. The penetration of the calcium nitrate solution into near-surface sediment is regarded as crucial for this process, as it eliminates hydrogen sulfide and enables binding to Fe oxyhydroxides, which can later transform into vivianite. Long-term treatment thus favors the formation of stable, mineral phosphorus bindings, keeping total phosphorus in deep water permanently at very low levels.

At Jörne Meerke, targeted incubation experiments were conducted by lanaplan GbR within the project. Sediment cores were examined before and shortly after the first calcium nitrate dosing. In the samples taken after treatment, a pronounced decrease in soluble phosphorus fractions was observed. Mineralogical investigations found no vivianite there, but evidence of calcium-bearing phases suggests the onset of apatite-forming processes. Since treatment had only just begun at that time, the absence of significant vivianite amounts is plausible.

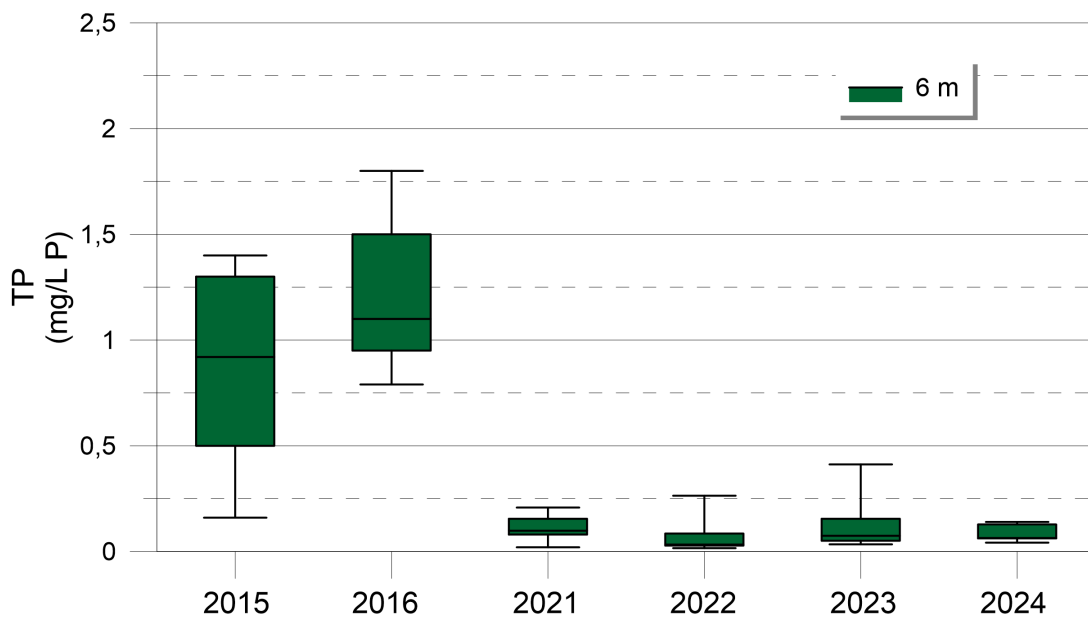


Figure 12: Yearly distribution of total phosphorus concentrations (6 m depth) in Schäfersee before treatment (2015–2016) and during the project period (2021–2024).

In the shallower Fennsee, uniform distribution of nitrate and oxygen dosing throughout the water column led to a general stabilization of the phosphorus budget. The reduction of phosphorus concentrations in

deep water suggests that iron(III) likely acts as a binding partner there. Due to persistently oxic water conditions, an iron(III) phosphate binding is probable, even though anoxic microzones can occur within the sediment itself.

6.6 Microbiological Findings

Microbiological investigations provide a detailed picture of how the composition and activity of microbial communities in the treated water bodies changed as a result of controlled oxygen and nitrate application. They focused on the extent to which dominant metabolic processes shift from reductive to oxidative conditions and the roles of nitrifying, denitrifying, and methanogenic microorganisms.

Schäfersee Microbiological analyses of Schäfersee show a largely stable composition of the microbial community over the entire treatment period. Even before the project began, the lake had been treated with the Schäfersee-Verfahren® for several years, so that an adapted sediment community had established. Evaluation of 16S rRNA sequence data shows that sediments are dominated by *Proteobacteria*, especially *Gammaproteobacteria*, which are known for heterotrophic denitrification (Xu *et al.*, 2014). Similar dominance patterns have been reported in other studies of calcium nitrate application (Tang *et al.*, 2018; Yang *et al.*, 2022). Methanogenic archaea of the order *Methanosarcinales* occurred only at low relative abundance and declined slightly over the treatment period, corresponding to decreasing methane concentrations in porewater and deep water.

Low-level DNA traces of *Microcystis* spp. were detected in Schäfersee sediments. These detections refer exclusively to sediment samples and are to be interpreted as remnants or persistent signals of earlier inputs, not as evidence of active pelagic populations. In the epilimnion, neither microscopic analyses nor HPLC or qPCR investigations revealed the presence of microcystin-producing cyanobacteria; the toxin microcystin-LR also remained below the detection limit of $0,1 \mu\text{g L}^{-1}$. This confirms that, despite nitrate and oxygen addition, there was no stimulation of toxigenic cyanobacteria in Schäfersee. Reference to the theoretical considerations of Hellweger *et al.* (2022) underscores that the supplementary investigations primarily served to scientifically exclude potential risks.

The findings suggest that microbial communities in the sediment can flexibly switch among oxygen, nitrate, and sulfate respiration and that denitrification processes are carried out by the existing populations. A fundamental restructuring of the microbial community was not required to implement the redox-based processes, indicating a stable, adapted sediment ecology.

Fennsee In the untreated state, anaerobic microorganisms catalyzing fermentation, sulfate reduction, and methanogenesis dominated in Fennsee. This was reflected in elevated sulfide concentrations and the lake's characteristic odor. After introduction of the Schäfersee-Verfahren®, the composition of the sediment community changed markedly: Nitrate-respiring and sulfur-oxidizing bacteria such as *Dechloromonas*, *Thiobacillus*, and *Sulfuritalea* increased in relative abundance, while methanogenic archaea,

especially *Methanosaeta*, declined significantly. This development indicates a targeted shift of the redox balance toward oxidative processes.

In parallel, TU Berlin documented a clear change in water chemistry. Sulfate concentrations rose in 2024 to between 75 and 120 mg L⁻¹ after being below 25 mg L⁻¹ in the previous year, while H₂S was only briefly detectable at the beginning of the year. At the same time, nitrate concentrations in the water column remained stable below 2 mg L⁻¹ NO₃-N, and dissolved organic carbon (DOC) in deep water decreased from 27,5 to 13–18 mg L⁻¹. These developments indicate intensified heterotrophic nitrate respiration and a transition to oxidative conditions throughout the sediment–water system.

Accompanying metagenomic analyses showed an increase in functional genes involved in nitrate respiration, demonstrating that the supplied nitrate is microbially utilized and does not decrease merely by diffusion or chemical reaction. In addition, more genes for oxygenases were detected, enabling microbial degradation of organic substances under oxygenated conditions. Overall, the findings show that the method in Fennsee leads to a lasting shift in microbial metabolic activity toward nitrate- and oxygen-based processes and thus creates a central prerequisite for long-term stabilization of the redox milieu.

Jröne Meerke From Jröne Meerke, only frozen surface sediment samples (0–5 cm) are currently available, which were archived for further microbiological investigation. Samples were collected by the project partner and delivered to TU Berlin for later analysis. An evaluation is still pending, as work during the study period prioritized gas measurements and metagenomic data from Fennsee. Given the similar physico-chemical initial conditions, it is nevertheless reasonable to assume that microbial processes at Jröne Meerke will shift comparably toward oxidative and nitrate-based metabolic pathways.

Cyanobacteria and Cyanotoxins Against the backdrop of the scientific discussion on interactions between nitrogen and phosphorus limitation (Hellweger *et al.*, 2022), it was examined whether nitrate and oxygen supply within the Schäfersee-Verfahren® would favor growth or toxin production of cyanobacteria, in particular *Microcystis* spp. TU Berlin established molecular (PCR, qPCR) and analytical (HPLC) methods to detect the *mcyA* gene and the toxin microcystin-LR.

In Schäfersee surface water, neither *Microcystis* nor microcystin-LR could be detected above the limit of detection (LOD = 0.1 µg L⁻¹); microscopic phytoplankton analyses and fluorometric chlorophyll measurements corroborated this finding. At Fennsee, neither the *mcyA* gene nor microcystin-LR were detected. In 16S rRNA analyses of the sediment, only minimal proportions of potentially toxin-producing cyanobacteria were found (*Microcystis* ≈ 0.002 %, *Nostoc* and *Planktothrix* even lower).

The data consistently show that the Schäfersee-Verfahren® does not promote the analyzed toxigenic cyanobacteria. Cyanobacterial DNA fragments occasionally detected in sediments can be interpreted as resting forms and showed no ecological relevance for the pelagic assessment in this study.

Assessment Taken together, the microbiological investigations demonstrate that the Schäfersee-Verfahren® induces a targeted shift in microbial metabolic processes in sediments. Regular supply of nitrate and oxygen largely suppresses sulfate- and methane-based reductive processes while strengthening oxidative and denitrifying processes. As a result, sediments develop a more stable redox milieu with lower methane formation and reduced hydrogen sulfide production. At the same time, no negative effects on microbiological diversity or stimulation of toxin-producing cyanobacteria were found. Overall, the results support the assumption that the method leverages microbially mediated processes to stabilize the sediment–water interface in the long term and sustainably improve water quality.

6.7 Climate-Relevant Effects

Reducing methanogenesis in anoxic deep water represents a central climate-relevant effect of the Schäfersee-Verfahren®. At Schäfersee, where the corresponding gas measurements were conducted, a pronounced decline in the formation of specific gases was observed after the start of calcium nitrate dosing. Within hours to days, H₂S production in deep zones decreased sharply, as evidenced both analytically and organoleptically: no hydrogen sulfide odor was detectable in deep-water samples—even with sediment fractions present. This indicates a far-reaching reduction of sulfate respiration and thus of H₂S emissions.

In parallel, microbiological analyses by TU Berlin documented a shift in microbial community structure, particularly in Fennsee, where treated and untreated states could be compared. Methanogenic archaea decreased, while nitrate- and oxidation-based metabolic groups increased.

This provides evidence that stabilized conditions influenced by nitrate and oxygen significantly restrict methanogenic activity in the sediment.

Experiments conducted by TU Berlin at Schäfersee support this finding quantitatively. Over the treatment period, concentrations of dissolved methane in sediments declined substantially. Subsequently, occasional transient increases were observed in midsummer, presumably due to dosing pauses and temporary thermal stabilization of the water column. This underscores the importance of continuous treatment to maintain stable redox conditions under ongoing inputs of untreated stormwater.

Nitrous oxide (N₂O) could be detected in the deep water of Schäfersee directly above the sediments as a natural intermediate of denitrification shortly after dosing. In the following year, nitrous oxide analyses at different depth levels were conducted and gas traps used; however, unlike methane, nitrous oxide could not be detected within the examined concentration range. At Fennsee, nitrous oxide was likewise not detected directly above the sediment, possibly due to controlled dosing with much lower nitrate concentrations applied. These findings indicate that nitrate application in the investigated lakes does not cause relevant incomplete denitrification processes, although further studies focusing on detailed nitrous oxide budgeting are still recommended.

Methane (CH₄) has roughly 28–34 times the global warming potential of carbon dioxide (CO₂) over 100 years (GWP₁₀₀) and about 80–83 times over 20 years (GWP₂₀) (Intergovernmental Panel on Climate Change (IPCC), 2023). Inland waters are therefore considered significant methane sources and play an underestimated role in the global carbon cycle (Aben *et al.*, 2017; Wen *et al.*, 2018). As early as Grossart *et al.* (2011) showed, methanogenic processes can occur even in oxic layers. The pronounced reduction of these processes achieved by the Schäfersee-Verfahren® thus has global climate relevance beyond local water protection.

The results to date show that methane production in the sediment and emission to the atmosphere at Fennsee were strongly reduced during treatment phases, even though short-term decreases in effectiveness were observed during summer stratification. The method thus makes a measurable contribution to mitigating climate-relevant greenhouse gases and to the ecological stabilization of urban waters. A further budgeting of avoided methane emissions in CO₂ equivalents can be determined in future work.

6.8 Technical and Process Insights

A key outcome of the project is the development of a fully integrated process control system for water body treatment. The stationary installations realized in the project enable demand-driven, remote-controlled dosing of calcium nitrate and allow flexible adaptation to hydrological and chemical boundary conditions in real time. This is the first time a water therapy approach has been implemented in which measurement, evaluation, and control are directly coupled.

- *Fennsee*: Container installation with underground distribution and turbojets; event-driven pulse dosing during heavy rainfall.
- *Jröne Meerke*: Integration of the drinking water network as an oxygen source; micro-cyclical dosing strategy with daily to bi-daily minimal amounts.
- *Schäfersee*: Pontoon operation as reference; planning of a shore-based station for continuous application.

The system is based on continuous acquisition of measurement data (oxygen, redox potential, temperature, nitrate, ammonium) at 10 min intervals. These data are automatically evaluated via a web-based platform so that dosing amounts can be adaptively adjusted to the current process states and the specific needs of each water body. Process control thus enables a *dynamic water therapy* in which interventions do not follow fixed schedules but are based on actual chemical and physical changes.

For illustration, exemplary online data are shown below that demonstrate the functionality and responsiveness of the automated control systems. Both examples highlight typical challenges of urban and peri-urban waters with differing hydraulic and trophic conditions.

The figures presented are screenshots from the web-based control and monitoring system, the central *Control Center*, through which sensor data are recorded, graphically processed, and visualized in real

time. The same platform is used for remote control of the dosing systems, enabling interventions to respond immediately and specifically to current changes in water parameters.

Fennsee: Reactive Pulse Dosing After a Heavy Rainfall Event. Heavy rainfall events place special stress on inner-city waters. Through stormwater sewers, surface water heavily loaded with organic material and nutrients enters the systems, often accompanied by temperature jumps and strong turbidity. The result is a rapid increase in biochemical oxygen demand throughout the water column, so that even previously stable oxygen conditions can collapse within hours. A typical example occurred on 9 September 2024: within half a day, oxygen in Fennsee dropped from previously 3–6 mgL⁻¹ to nearly zero. On the following day, the container installation control initiated a reactive pulse dosing. Three doses of 200 L calcium nitrate each were sufficient to bring about a clear recovery of oxygen conditions within a few days. Figure 13 shows the temporal development of this event. The example illustrates that automated control can buffer short-term stress caused by external events and maintain stable oxygen dynamics even under extreme conditions.

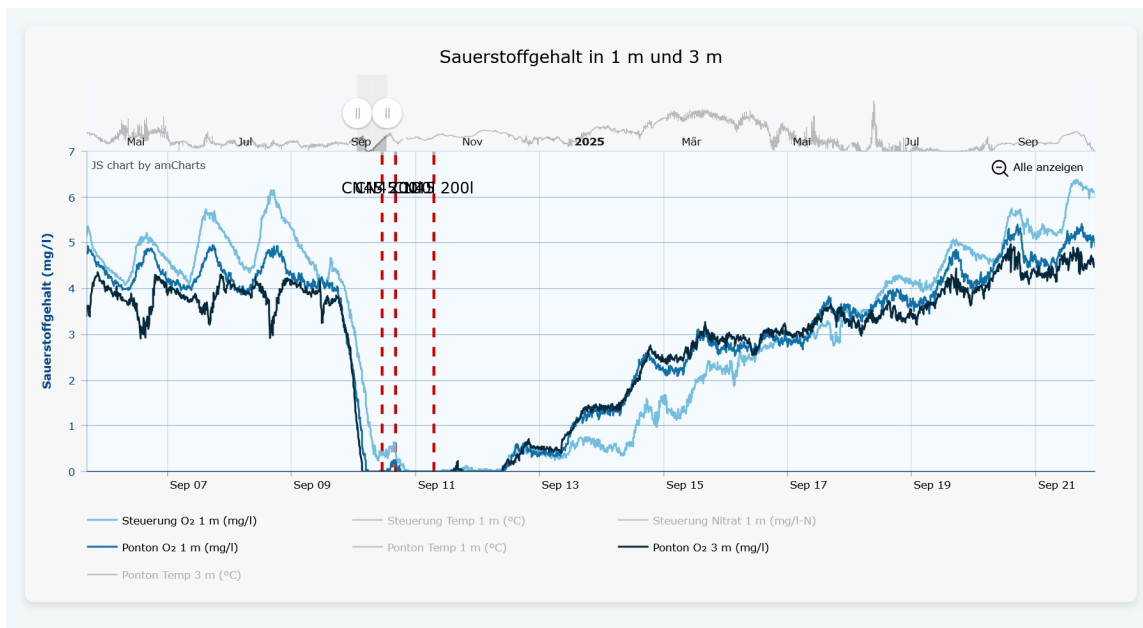


Figure 13: Fennsee: Reactive oxygen stabilization after heavy rainfall via pulse dosing (online data, 10 min interval).

Jröne Meerke: Gradual Increase of Redox Potential. At Jröne Meerke, a different control approach was pursued, based on continuous but small nitrate additions. The goal was a targeted, gradual increase of the redox potential in the deep zone to permanently suppress reductive processes. Initially, daily dosing of around 10 L calcium nitrate was applied; with increasing system stabilization, the dosing interval could gradually be extended to two days without loss of redox effect. This continuously reduced nitrate supply produced a lasting stabilization of chemical conditions over several weeks: Redox potential was progressively shifted into the positive range while ammonium concentrations declined. This development shows that even small, demand-driven doses suffice to shift the sediment–water

interface into a mildly oxidizing milieu and prevent the release of reduced species (NH_4^+ , Fe^{2+} , Mn^{2+}). The online data in Figure 14 illustrate this relationship and demonstrate the efficiency of the gentle, micro-cyclical dosing strategy.

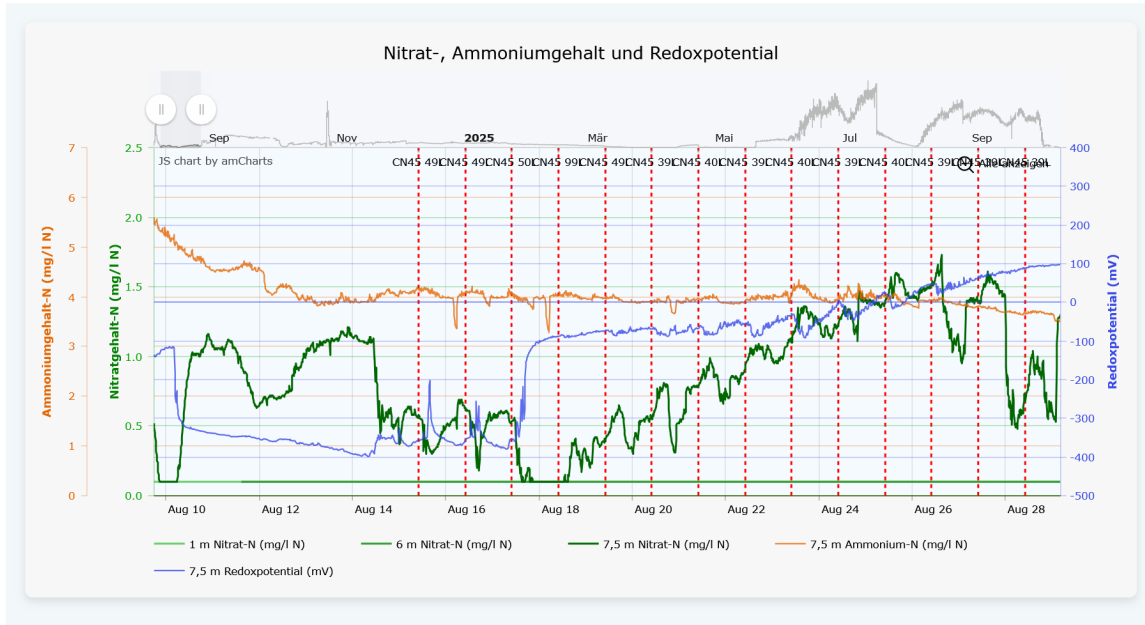


Figure 14: Järone Meerke: Development of nitrate, ammonium, and redox potential under daily pulse dosing (live data from online monitoring).

Extensive online data series are also available for Schäfersee, documenting the course of oxygen and redox potential. Continuous control has not yet been implemented there, as treatment currently takes place in three time-limited dosing phases per year. During these approximately two-week applications, deep water is pre-dosed in a targeted manner, which already achieves a marked stabilization of the redox potential.

With a planned shore-based dosing installation, continuous, measurement-driven control would be possible in the future. By directly coupling to sensor data (redox and nitrate probes), the dosing regime could be dynamically adjusted and material input further optimized. This would not only enable even more precise stabilization of the milieu but also reduce material consumption and increase operational reliability.

7 Progress in the Field of the Project at Other Institutions

During the project term, several international studies were published that address the use of nitrate for redox stabilization and remediation of eutrophic or impacted water bodies. These works confirm the fundamental effectiveness of nitrate-based methods and expand the understanding of their ecological effects.

As early as the 1970s, the use of nitrate for biochemical oxidation of reduced sediments was first described (Ripl, 1976). The principle of using nitrate as an alternative electron acceptor to suppress anaerobic processes forms the conceptual basis of many modern remediation methods, including the Schäfersee-Verfahren®.

In recent years, various research groups worldwide have investigated and further developed new applications of this approach. For example, Kowalczywska-Madura *et al.*, 2024 demonstrated that continuous nitrate treatment of the hypolimnion in a hypereutrophic lake leads to a significant improvement in oxygen conditions, a reduction in phosphorus release, and stabilization of water quality. It was shown that the method also operates stably in the long term and shortens or completely prevents phases of cyanobacterial blooms.

Further investigations focused on the targeted supply of calcium nitrate in combination with oxygen enrichment, particularly for odor control and redox stabilization in organically loaded sediments. Studies such as Y. Zhang *et al.*, 2024, Wang *et al.*, 2024, and S. Zhang *et al.*, 2024 examined both laboratory and field applications in which calcium nitrate achieved sustained suppression of reductive processes and an improvement in phosphorus binding. At the same time, under certain conditions, indications of metal mobilization were observed, underscoring the need for precise dosing strategies and continuous monitoring. However, the majority of published work to date has been conducted at laboratory or reactor scale or has illuminated individual sub-aspects, so that the field findings obtained in the present project provide an ideal and practice-oriented complement to the international state of research.

Earlier work on the effects of nitrate and oxygen on microbial turnover (W. Li *et al.*, 2019; Zhou *et al.*, 2020; L. Li *et al.*, 2021; Tang *et al.*, 2018; Yang *et al.*, 2022) has also made important contributions to understanding processes in sulfide-rich or heavily organic-loaded sediments. They show that nitrate acts not only as an oxidizing agent but also promotes specific microbial communities that support the degradation of organic pollutants.

In summary, these publications demonstrate that nitrate-based methods are increasingly recognized internationally as a *nature-based solution* for redox stabilization and pollutant reduction. The results confirm the findings achieved in the present project regarding the effectiveness, controllability, and environmental compatibility of nitrate-supported process control and underline the importance of a precise, adaptive control strategy, as implemented for the first time in the Schäfersee-Verfahren®.

7.1 Utilization and Outlook

The Schäfersee-Verfahren® has been successfully validated as a permanently applicable, automated system for redox stabilization of urban water bodies. Its application enables targeted control of the redox milieu, reduces the formation of reductive gases, and contributes to the stabilization of internal material cycles. For the first time, a practical method is thus available that is particularly suitable for rainwater-affected, urban, and eutrophic waters as well as for shallow, highly organically loaded lakes.

The results achieved form the basis for further technical implementation in municipal water management. The transfer of the method to additional sites with similar load conditions is planned. Follow-up projects are currently being prepared in Hanover, Braunschweig (urban park lakes), and in North Rhine-Westphalia.

In practical water protection, there is a clear need for solutions to treat stormwater retention and urban water bodies that regularly suffer from oxygen deficiency and odor nuisances. The Schäfersee-Verfahren® offers a proven, resource-efficient approach that can be combined with existing infrastructure. The project results show that this provides new options for municipalities, particularly where no economically viable remediation methods have previously existed.

In the long term, there is potential for applying the method to other types of water bodies such as reservoirs, dams, and retention basins. Through its combination of simple technology, high automation level, and data-driven control, the Schäfersee-Verfahren® provides a robust and transferable solution for sustainably improving the quality of urban water bodies.

8 Summary and Conclusions

The fundamental objective of the project was the stabilization of sensitive, redox-dependent aquatic systems through targeted treatment of the deep-water body. The focus was not on classical nutrient elimination, but rather on the restoration of a stable, oxidizing milieu in the hypolimnion — as the basis for all further biogeochemical processes.

At Schäfersee, it was demonstrated that the application of calcium nitrate does not induce any adverse effects on the system. Neither toxic reaction products nor heavy metal accumulations occurred; rather, it became evident that the addition of nitrate and the associated oxygen supply completely suppress reductive, potentially harmful processes. As a result of the oxidation of ammonium and sulfide compounds, toxic substances such as hydrogen sulfide are eliminated, while at the same time nitrate- and oxygen-dependent enzyme systems (e.g., monooxygenases) promote the microbial degradation of organic substances. This reactivates natural sediment degradation and stabilizes the overall system in the long term. Particularly noteworthy is the unexpectedly long-lasting oxygen enrichment in the deep water of Schäfersee, observed over periods of up to nine months — a clear indication of sustained buffering of the redox potential and the re-establishment of oxidative sediment zones. Complementary groundwater investigations showed no elevated nitrate concentrations at any time, confirming the local retention effect and ecological safety of the method.

During the course of the project, the application of the Schäfersee-Verfahren® was extended to additional types of water bodies. At Jörne Meerke, it was shown that even a strongly stratified deep lake can be transformed from a reducing into an oxidizing milieu within a few weeks through targeted, small-dose nitrate additions. Micro-cyclical dosing there led to a continuous increase in redox potential and a pronounced decrease in ammonium in the deep water. In contrast, at Fennsee, a shallow, polymictic system was successfully treated. The areal dosing via an underground pipe distribution network enabled homogeneous mixing and stabilized the redox level throughout the entire water column. The system responded robustly even to heavy rainfall events: short-term oxygen deficits could be compensated within a few days through targeted pulse dosing.

The change in the chemical milieu inevitably altered the living conditions for microorganisms and higher organisms. The restoration of an oxidizing hypolimnion created habitats that had previously been permanently anoxic and therefore uninhabitable. No negative effects on flora or fauna were observed in the treated water bodies. Rather, it can be assumed that biodiversity is developing toward a more stable and species-rich community. Initial indications of such a habitat shift are provided by microbiological analyses showing an increase in nitrate-respiring bacteria and a marked decrease in methanogenic archaea. In parallel, no relevant nitrous oxide emissions were detected; nitrate dosing did not lead to measurable accumulation of N_2O , indicating largely complete denitrification. The substantial reduction of methane formation in the sediment and the significantly diminished emissions to the water surface also make a measurable contribution to mitigating climate-relevant greenhouse gases.

In addition to targeted stabilization of the redox potential and suppression of methanogenic processes, another initially unexpected effect emerged during the project: the altered chemical conditions led to a marked decrease in dissolved and mobilizable phosphorus fractions. This observation was not a primary project objective at the outset but proved to be a key finding concerning the long-term effectiveness of the method. Stabilization of the redox milieu created conditions under which dissolved phosphorus in the sediment could again be immobilized. At Jörne Meerke, incubation experiments conducted by lanaplan GbR demonstrated a reversal of the flux direction: a sediment that had previously acted as a phosphorus source became a stable phosphorus sink within a few weeks. This development was clearly confirmed by geochemical and mineralogical analyses of TU Berlin, indicating the formation of iron(II) phosphate (vivianite) and calcium-bearing phosphate minerals. Long-term data from Schäfersee likewise show a decline in total phosphorus content, suggesting sustained phosphorus binding in the sediment. Thus, it is proven that redox stabilization not only eliminates reductive processes but also indirectly improves internal phosphorus dynamics.

Overall, it is evident that the combined dosing of nitrate and oxygen leads to comprehensive stabilization of the chemical and biological equilibrium in treated water bodies. The Schäfersee-Verfahren® restores oxidizing conditions, degrades reductive substances, activates microbial degradation processes, and eliminates toxic compounds. It therefore functions both as a technical remediation measure and as an ecological regeneration strategy.

For future development, there is potential in establishing permanently sensor-supported systems that enable adaptive regulation based on online data (redox, nitrate, oxygen). Furthermore, the long-term stability of mineral phosphorus binding and the effects on biodiversity should be further investigated. In addition, quantification of avoided methane emissions in CO₂ equivalents and assessment of potential nitrous oxide fluxes should be part of future studies to comprehensively account for the climate-relevant effects of the method. The procedure has proven to be a scalable, resource-efficient, and environmentally compatible tool for the remediation of eutrophic water bodies and can make a significant contribution in the future to reducing internal nutrient loads and climate-relevant emissions.

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