Vanadium removal from drinking water by fixed-bed adsorption on granular ferric hydroxide

Carsten Bahr¹ | Martin Jekel² | Gary Amy³

¹Research and Development, GEH Wasserchemie GmbH & Co. KG, Osnabrueck, Germany
²Department of Water Quality Control, Technical University of Berlin, Berlin, Germany
³Environmental Engineering and Earth Science, Clemson University, Clemson, South Carolina, USA

Correspondence
Gary Amy, Environmental Engineering and Earth Science, Clemson University, Clemson, SC 29634, USA.
Email: gamy@clemson.edu

Abstract
The metal vanadium (V), often present as pentavalent oxyanion vanadate, can be present in groundwaters worldwide due to natural origin. While there are presently no US drinking water standards for vanadium, the German Environmental Protection Agency has defined a guidance value of 4 μg/L in drinking water. Impacted water suppliers need an effective and selective treatment process for meeting this value. In 2020, an extended efficiency test (EET) was completed successfully at a water works in Daun, Germany using GEH®, Granular Ferric Hydroxide, an adsorbent that has been in use for over 20 years in several thousand treatment plants worldwide, primarily for removal of arsenic present as arsenate, with chemical similarities to vanadate. An EET, performed in a treatment plant with a flow of 34 m³/h over 13 months, demonstrated reliable removal of vanadium, present at 28 μg/L, down to the limit of quantification (2 μg/L). Thus, for water supplies with vanadium occurrence and a similar water quality, GEH® may provide an effective treatment option.

KEYWORDS
fixed-bed adsorption, GEH®, granular ferric hydroxide, vanadium removal, water quality, water treatment

1 INTRODUCTION

1.1 Vanadium occurrence in groundwater

Vanadium is a transition metal and can be found in different minerals in an aquifer. Natural weathering processes induce a transfer to groundwater, with a typical occurrence as the pentavalent redox species vanadate-oxyanions (H₂VO₄⁻ and HVO₄²⁻ in the neutral pH range) (Gustafsson, 2019). Vanadate shows strong chemical similarities to phosphate (H₃PO₄⁻ and HPO₄²⁻) and arsenate (H₂AsO₄⁻ and HAsO₄²⁻). Figure 1 shows a distribution diagram for a low concentration of vanadium at 30 μg/L, with the predominant species being H₂VO₄⁻ at neutral pH (Blackmore et al., 1996). The pKₐ₂ is close to 9, thus the species HVO₄²⁻ increases in concentration with increasing pH but will not be dominant at pH values below about 9.

Vanadium is present as a natural substance in groundwaters worldwide, for example, in the United States, Canada, China, and in several European countries (Germany, Italy), depending on geological conditions, for example, volcanic rocks as geogenic source of...
vanadium (Vasseghian et al., 2021; Wright & Belitz, 2010).

A survey by the Environmental Working Group (EWG) in the United States indicates a relatively wide occurrence of vanadium in tap waters, with values exceeding the EPA’s health reference value of 21 μg/L in 10 US states for 122 utilities. Vanadium was detected in tap waters (analytical limit of detection was not specified) in all US states and about 7000 utilities serving 210 million people. The sources and robustness of the vanadium dataset are also unclear and the survey by EWG is not peer-reviewed (EWG, 2019).

US-EPA conducted an extensive study under the Unregulated Contaminant Monitoring Rule, UCMR, including the occurrence of vanadium (US-EPA, 2017). The minimum reporting level, MRL, was 0.2 μg/L and the Health Reference Level, HRL, is set at 21 μg/L. The occurrence data are summarized as follows: 60% of ca. 70,000 samples showed vanadium concentrations above the MRL. The HRL was exceeded by 2.7% in all samples and in 3.3% of samples from public water supplies.

For example, different regions in Germany with elevated vanadium in groundwaters are the Vulkaneifel, the Vogelsberg, and the Westerwald, with groundwaters having oxic redox conditions and with volcanic minerals. In a recent study, the occurrence and origin of vanadium were investigated in detail in the region of the Ringseitert volcanic complex southeast of the community Kirchweiler (District of Vulkaneifel). Samples of the volcanic rocks were analyzed, confirming elevated vanadium levels, and indicating the phosphate mineral fluoro-apatite as a geogenic source of vanadium. This finding explains the higher molar levels of phosphate (compared with the pentavalent vanadium) in the groundwaters (Härter et al., 2020).

Even though elevated levels of vanadium can have adverse health effects, the present German drinking water directive does not include a regulatory standard. However, the German Federal Environmental Agency has established a guidance value of 4 μg/L, based on human toxicology (ATSDR, 2012; Six, 2008) and a maximum value of 20 μg/L, indicating a need for introducing measures to reduce the vanadium content of drinking waters. Water suppliers, impacted by vanadium presence, are forced to meet these values, based on the principle of precaution, as set by the German drinking water directive.

The WHO Guidelines for drinking water quality do not contain a limit value for vanadium (WHO, 2017). Vanadium is not regulated in the United States, although it is listed as a contaminant of concern and is on the US-EPA Contaminant Candidate List 3 (CCL 3). The California Office of Environmental Health Hazard Assessment (OEHHA) has published a proposed notification level for vanadium at 15 μg/L in drinking water (OEHHA, 2000).

The American Water Works Association, AWWA, offers information on what is in tap water, including vanadium. The EPA has tested for vanadium in the UCMR 3, the third Unregulated Contaminant Monitoring Rule. If the findings indicate a wider occurrence above the regulatory standards in discussion, vanadium may be included in regular monitoring and regulations; it is mentioned that ongoing exposure of vanadium values above 21 μg/L may lead to negative health effects (AWWA, 2021).

### 1.2 Vanadium drinking water regulations

Thus, vanadium is of concern in some areas of the United States and most probably in other parts of the world (EWG, 2019).

#### 2 PROCESSES FOR REMOVAL OF VANADIUM FROM DRINKING WATERS

Most of the water suppliers encountering a vanadium problem in Germany are small systems, which may have
otherwise no problematic substances in their raw waters and either do not use treatment or only a simple treatment train. For this reason, an essential consideration for vanadium removal is the need for a simple and safe process with little maintenance.

Based on the chemical similarity of vanadate and arsenate, it can be expected that treatment processes for arsenic can be applied for vanadate removal in general (Hering et al., 2017).

Therefore, the following processes can be identified as potential solutions for vanadate removal.

- Coagulation with ferric salts
- Adsorption on granular ferric hydroxides and other metal-oxide adsorbents
- Ion exchange resins
- Membrane processes (nanofiltration and reverse osmosis)

A study on removal of arsenic, silica, and vanadium with four different iron-based adsorbents in a pilot plant at Weatherford, Oklahoma, indicated a preferential uptake of vanadium versus arsenic and silica (Arora et al., 2007). While the breakthrough of vanadium occurred later than for arsenic for all media tested, it did not include granular ferric hydroxide, GEH®. A recent review article summarizes all relevant publications on removal of vanadium by sorption processes, including metal oxides and metal hydroxides, zero valent iron, chitosan, activated carbon and biochar, anion exchangers, other organic functionalized materials and other inorganic materials (Leiviskä, 2021). The reuse of loaded and exhausted adsorbents is also considered, with regeneration by different chemical solutions. The author concludes that more research is needed for developing practical solutions as the effects of some important parameters such as pH, V speciation, competing species, and temperature are not fully understood. The available data indicate, however, that vanadium removal is an interesting new challenge in water treatment. The different studies cited in this review show that oxyanions like vanadate, arsenate, and phosphate show a very high affinity to ferric hydroxide surfaces (Peacock & Sherman, 2004). These anions are removed selectively from the water, with binding on ferric hydroxide sludge in coagulation or by attachment to granular ferric hydroxide in a fixed-bed adsorber. The different oxyanions are competing during the selective removal, with the effect that increased phosphate (and/or arsenate) concentrations in the raw water reduce the capacity of any adsorbent for vanadate. In a recently published study, it was shown that the affinity of adsorption onto GEH® is higher for vanadium than for arsenic and phosphorus (Dabizha et al., 2020). On the other hand, another study investigating the adsorption competition for another iron-based adsorptive media (E33) suggested that arsenate is better removed than vanadate (Sorg et al., 2021).

Based on an EPA report on assessing arsenic removal by metal (hydr-)oxide adsorptive media using rapid small-scale column tests (RSSCTs), the results include the removal of vanadium, simultaneously present in the waters investigated. The study shows that all media tested remove this metal. Granular ferric hydroxide, now called GEH®, removed vanadium (at 9 μg/L initial concentration) to below 1 μg/L with higher bed volumes (up to 100,000 BV treated) than any other media (Westerhoff et al., 2008).

2.1 Extended efficiency test (EET)

During treatment of drinking waters in Germany, treatment chemicals and disinfection processes can be applied only if they are included in a specific list by the German Environmental Agency. If an application is basically evaluated as sufficient, the next step is to conduct an “Extended Efficiency Test” (EET). This test procedure lasts 1–3 years and is evaluated by an external reviewer. It is performed on-site at a water supplier at full scale and is supervised by the regional health agency. Other water suppliers can apply this treatment substance in full-size tests for 2 years, based on the exemption regulations. If a product standardization by European Union or Germany is available, the treatment substance will be introduced finally into the list mentioned above.

2.2 The GEH®-adsorption plant of the waterworks of Daun

2.2.1 Characterization of groundwater and water supply

The drinking water supply in the community of Daun is organized by the Association of the Group Water Works Daun. There are 21 water treatment plants, with the raw water collected from 35 springs and wells. About 25,000 inhabitants receive the water in 55 communities and settlements.

In some of the wells, elevated vanadium concentrations above 20 μg/L were found, inducing an action plan by the water supplier. After detailed analysis and in cooperation with the health authorities, a first pilot adsorption test was performed at the pump station of Kirchweiler. The test results in the years 2018–2019 showed that
GEH® is generally suitable to remove vanadium completely from the well water during the first operational phase of fixed-bed adsorption. In the second phase, a slow and gradual increase of the filter effluent concentrations was noted, typical for fixed-bed adsorption processes.

An EET was done at the elevated reservoir at Ernstberg. The raw water used is a mixture from two sources with variable flows and mixing ratios. One source is the spring at Schlierbach, with a mostly fixed flow of 125 m³/day and an average operational time of 8 h/day. The other source is the well Steinborn Hipperswies with variable flow of up to 480 m³/day, but with a typical flow of 150 m³/day and an operational time of 10 h/day.

The raw water is, with the exemption of vanadium, of high quality (see Table 1). It can be characterized as a soft water with low content of dissolved minerals, which needs stabilization by removal of carbon dioxide (saturation index – 0.78). This water contains a relatively high content of silicate, and the occurrence of phosphate at 0.5 mg/L confirms the former investigations on the geogenic origin of vanadium.

### 2.3 | GEH® granular ferric hydroxide

GEH® is a synthetically produced granulated ferric hydroxide, which has been used successfully for more than 20 years in drinking water treatment worldwide for selective removal of arsenic (Banerjee et al., 2008; Hering et al., 2017). The adsorption material has a high porosity and a high specific surface of about 300 m²/g (BET-method). The grain size range is 0.2–2 mm and the bed density is 1150 kg/m³ after backwashing of the adsorber bed (GEH Wasserchemie, 2021).

The product quality meets the specifications of the European Norm EN 15029:2012. Granular Ferric Hydroxide can be applied in German drinking water plants.

### Table 1: Water quality analysis of the raw water at the elevated reservoir Ernstberg

| Specific water quality parameters | Raw mixed water (typical values) | Units | Method |
|----------------------------------|----------------------------------|-------|--------|
| Vanadium                         | 30                               | µg/L V| DIN EN ISO 11885 (E22) |
| Phosphate                        | 0.52                             | mg/L PO₄| DIN EN ISO 6878 (D11) |
| Silica, soluble                  | 31                               | mg/L SiO₂| DIN 38405 (D21) |
| Arsenic                          | <1                               | µg/L As| DIN EN ISO 11969 (D18) |
| Uranium                          | <1                               | µg/L U | DIN EN ISO 17294-2 (E29) |

| General parameters |
|--------------------|
| Temperature         | 7.7°C                           | DIN 38404 (C4) |
| pH value            | 7.6                             | DIN EN ISO 10523 |
| Turbidity, qualitative | Clear                        | DIN EN ISO 7027 (C2) |
| Conductivity, 25°C  | 245 µs/cm                       | DIN EN ISO 27888 (C8) |
| Dissolved oxygen    | 9.7 mg/L                        | DIN ISO 17289 (G25) |
| Total hardness      | 0.98 mmol/l                     | Calculated |
| Bicarbonate         | 1.9 mmol/L                      | DIN 38409 (H7) |
| Calcite dissolution capacity | 15 mg/L           | DIN 38404 (C10) |
| Calcium             | 25 mg/L                        | DIN 38406 (E3) |
| Magnesium           | 9 mg/L                         | DIN EN ISO 14911 (E34) |
| Sodium              | 5 mg/L                         | DIN EN ISO 14911 (E34) |
| Potassium           | 6 mg/L                         | DIN EN ISO 14911 (E34) |
| Iron                | <0.006 mg/L                    | DIN 38406 (E33) |
| Manganese           | <0.006 mg/L                    | DIN 38406 (E33) |
| Sulfate             | 11 mg/L                        | DIN EN ISO 10304-1 (D20) |
| Chloride            | 5 mg/L                         | DIN EN ISO 10304-1 (D20) |
| Nitrate             | 10 mg/L                        | DIN EN ISO 10304-1 (D20) |
| Fluoride            | 0.27 mg/L                      | DIN 38405 (D4) |
| TOC                 | 0.5 mg/L                       | DIN EN 1484 (H3) |
based on the national regulations, as specified in the list of treatment substances and disinfection processes (§ 11 of the German drinking water ordinance). GEH® is certified according to NSF/ANSI/CAN 61, Drinking Water System Components - Health Effects.

2.4 | Design and operation of the GEH-Plant

Adsorbers with GEH® correspond to the design and operation of conventional pressure filters used in rapid filtration with sand, or with activated carbon for adsorption. GEH® can be used in a single bed adsorber or in a group of units operating in parallel or sequential arrangements. The container materials consist of steel with an internal coating, stainless steel, or plastic (e.g., glass fiber reinforced resins). The filter nozzles are covered by a gravel layer, supporting the layer of GEH®. For operation, a filtration rate of 10–15 m/h is recommended (max. of 20 m/h) with an Empty Bed Contact Time (EBCT) of at least 3 min (GEH Wasserchemie, 2021; Driehaus, 2002).

The EET was performed at an existing filter plant, with water tested before pH increase by dolomite material. Out of three filter units, two were filled with 1500 kg of GEH® each and operated in parallel (Table 2). The plant was fed with 34 m³/h raw water (28 μg/L V), with an average time of operation of 16 h/day. Design and the operation of the plant were planned for a replacement of an average time of operation of 16 h/day. Design and the operation of the adsorber units showed an immediate complete removal of vanadium.

The plant was operated until March 3, 2020. The exchange of GEH® was done on August 28, 2019. The monitoring program included the documentation of operational data (water flows, pressure losses, backwash cycles, etc.), numerous water quality analyses (according to the German drinking water regulations), and material analysis of the fresh and loaded GEH®.

3 | METHODS

Water samples were taken from the inlet pipe (=raw water) and from the outlet pipes of both GEH filters (=treated water). Sampling procedure and sample preservation were conducted according to DIN EN ISO 5667-3 and DIN EN ISO 19458 by a laboratory accredited by the national accreditation body of Germany (DAkkS). The key parameter vanadium was analyzed by the ICP-OES method according to DIN EN ISO 11885. The limit of quantification (LOQ) was 2 μg/L V. A speciation analysis to distinguish between different oxidation states of vanadium was not conducted. The assumption of predominating vanadate was derived from speciation calculations done with the software Visual MINTEQ v.3.1 (https://vminteq.lwr.kth.se/). The analytical methods used for the other water parameters are indicated in Table 1.

At the end of the first operational period, one of the two filter units was sampled, and the loadings were determined by sorbent material analysis. The GEH® samples were collected with a soil sample probe. The samples included a representative mixed sample from the whole GEH®-bed as well as four samples taken at different bed depths.

The granules were analyzed by digestion with hydrochloric acid, and the elemental contents of vanadium (LOQ = 1 mg/kg), phosphorous (LOQ = 20 mg/kg), and arsenic (LOQ = 1 mg/kg) were measured by ICP-MS (ISO 17294-2). The determination of silica (calculated as SiO₂) was performed by borate digestion according to ISO 11885 (LOQ = 1 g/kg). The analytical data refer to dry matter (DM) according to EN 15934, with a DM-content of all GEH®-samples in the range of 60%–70%.

For modeling adsorption dynamics in fixed-bed adsorbers, several mathematical approaches are available. In a former study, it was demonstrated that

| TABLE 2  Design parameters for the GEH® adsorber |
|-----------------------------------------------|
| **Number of adsorbers** | 2 (operated in parallel) |
| Filter diameter | 1300 mm | 4.3 feet |
| Bed depth of adsorber | 1000 mm | 39.4 inches |
| Bed volume BV | 1325 L (both beds: 2650 L) | 46.8 ft³ (both beds: 93.6 ft³) |
| GEH® mass | 1.5 t (both beds: 3 t) | 1.65 ton (both beds: 3.3 ton) |
| Volume flow | about 17 m³/h for each filter | about 75 gpm for each filter |
| Filtration rate | about 13 m/h | about 5.3 gpm/ft² |
| Empty bed contact time (EBCT) | ca. 4 min | ca. 4 min |
vanadium adsorption on GEH® can be modeled successfully by a combination of a surface complexation model (CD-MUSIC) with the homogeneous surface diffusion model (HSDM) (Dabizha et al., 2020). In this study, we used the same set of parameters for modeling (i.e., complexation constants, diffusion coefficients, etc.) with the specific parameters of this project (i.e., metal concentrations, pH, GEH adsorber bed dimensions, flow rates, etc.).

4 | RESULTS OF THE EXTENDED EFFICIENCY TEST (ETT)

4.1 | General aspects

By comparison of water quality data before and after the GEH® adsorbers, it was demonstrated that selective vanadium removal occurred, and no changes in other characteristic of water composition were observed (pH value, conductivity, hardness, main cations and anions). However, as expected, phosphate and silicate were also removed from the raw water.

It was also shown that the GEH® does not elute problematic substances, like heavy metals or organic substances. In addition, the colony counts did not increase in water passed through the adsorber units.

Operation of both GEH®-adsorber beds proved to be quite simple and reliable. The pressure loss was below 0.1 bar and stable over operation time. The raw water was free from any turbid matter and a clogging layer was not formed; thus, a regular backwash of the units was not required. The GEH®-adsorber units provided constant effluent quality without outliers, despite changing inflow conditions (intervals in operation and different mixing ratios of the raw water). These observations confirm the long-time practical experiences with GEH® observed for arsenic removal as a very reliable process with low maintenance.

4.2 | Vanadium removal

Regular sampling of influent and effluent of the GEH®-filters revealed vanadium concentrations in the treated drinking water as a function of time and thus the characteristic breakthrough curve for this raw water (Figure 2). Vanadium concentrations in the filter influent (28–30 μg/L) were removed completely for a period of 3–4 months (down to below the LOQ of 2 μg/L V). Thereafter, a slow increase of the effluent concentration was noted, and the German drinking water guide value of 4 μg/L was reached after 140 days (first run) and 175 days (second run), see Figure 2. At this point of time, the GEH® must be exchanged with fresh material. Regeneration of the spent adsorbent is not recommended for exhausted GEH®, due to a limited efficiency of regeneration by sodium hydroxide and acid posttreatment. In the time frame of the EET, the filters were operated for some more weeks to demonstrate that the trend in concentration increase is slow, and a sudden breakthrough does not occur.

After 200 days of operation, the material was changed. The second test trial showed an analogous behavior with a nearly identical breakthrough curve, indicating good reproducibility of the results. After the end of the test period in March 2020, the GEH®-adsorber with the second material filling was further operated and the vanadium concentration increased only slowly and is still presently below the limit of 20 μg/L V for the German action value (July 2021). The typical, flat breakthrough curve for GEH® adsorbers offers the possibility for a suitable arrangement of filters (e.g., parallel filters with a lag in start-up time, or sequential filters with a change in the sequence after the
first filter is exhausted) to achieve a better use of the adsorber capacity and the extension of the filter use time (thus the number of bed volumes treated).

Breakthrough curves, independent from the plant design and operation, are frequently shown as a function of treated bed volumes (BV), and thus are normalized for comparisons with other data sets and plants. If these plots are shown for the breakthrough curves of both operational periods, we see that they are nearly identical and can thus be combined in one graph (Figure 3).

The specific treatment capacity (for achieving below $4 \mu g/L$) is about 30,000 BV, resulting in about 80,000 m$^3$ of treated water. This capacity is comparable to the practical experiences for GEH$^\text{®}$-plants for arsenic removal, if a similar water quality is encountered in terms of pH value, phosphate, and silicate concentrations (the main competitors to vanadium).

As shown in Figure 3, the model approach is also suitable for the present application to describe the breakthrough curve. This planning tool is available for future projects in designing adsorbers, based on water composition, for a reliable prediction of vanadium breakthrough.

5 | RESULTING LOADINGS

Analytical results show an average loading of 5.33 grams of vanadium per kg GEH$^\text{®}$ (DM) and a loading gradient was observed from the top to the bottom of the adsorber bed (Table 3), as expected. At the top of the bed, a loading of 7.66 g/kg was noted, while at the lower end of the column, the loading was below 1 g/kg, which relates to the flat form of the observed breakthrough curve.

Phosphate loading is on average 15.36 g/kg, confirming the strong adsorption competition between vanadium and phosphate. A comparison on a molar basis shows that vanadium is adsorbed more selectively, confirming the findings of the abovementioned study (Dabizha et al., 2020). Although the phosphate concentration is much higher than the vanadium concentration ($5.5 \mu mol/L \text{ PO}_4$ vs. $0.6 \mu mol/L \text{ V}$), the achieved vanadium loading is comparably high ($162 \text{ mmol/g PO}_4$ vs. $105 \text{ mmol/g V}$). Thus, we conclude that the phosphate species are less adsorbable on GEH$^\text{®}$ than the vanadate species for the pH value of this raw water at 7.6.

The loadings for arsenic on GEH$^\text{®}$ are quite low, due to very low influent concentrations below the LOQ of 1 µg/L. However, the high affinity of GEH$^\text{®}$ for arsenic leads to a significant enrichment in the solids, above the limit of detection. The SiO$_2$-content of loaded GEH$^\text{®}$ is about 76 g/kg or 7.6% by mass in the mixed sample, confirming adsorption or possible precipitation of dissolved silica on the GEH$^\text{®}$ surface (raw water content of 31 mg/L SiO$_2$).

From published papers, it is known that silica reduces arsenic adsorption significantly, likely by pore blocking (Swedlund & Webster, 1999). However, the results of the present study are not sufficient to determine whether oxyanion adsorption is negatively affected by silicate.

The loading data are comparable to the results of previous pilot tests at different locations in the Vulkaneifel region with geogenic vanadium (Bahr et al., 2019).

5.1 | Exchange and disposal of the loaded adsorption material

The loaded (spent) GEH$^\text{®}$ granules must be disposed, as regeneration and reuse are not planned. The water supplier as operator of the plant is the producer of waste and a safe and organized disposal must be planned.
Exchange is done by suction withdrawal of the adsorption material with a suitable truck with vacuum pumps, provided by a certified disposal company. The removal and new filling of an adsorber unit can be finished in 1 day, thus the operational stoppage is short.

Based on the average vanadium content of 5.33 g/kg, the loaded GEH® is considered to be a nonhazardous waste. However, the loaded material, in view of sustainability aspects, was designated as a waste with hazardous substances, according to the German waste regulations. It was disposed in a safe landfill for special wastes.

Costs of disposal in this project amounted to about 130 Euros per ton of material (ca. 136 $/ton). To compare these costs, we can use the costs known from the disposal of arsenic-containing adsorbents in Germany as a guide. The practical experiences with GEH® for arsenic removal indicate that the costs significantly vary regionally in the different federal states with a range of 300–800 €/ton (i.e., 314–837 $/ton). Therefore, the disposal costs can be considered relatively low in this project. However, this cannot be generalized to worldwide projects, since both the waste classification and the disposal route usually differ in all countries.

In the United States, such a waste is evaluated according to a TCLP (toxicity characteristic leaching procedure) test to ascertain whether it is classified as hazardous (US-EPA, 1992). Since, to our knowledge, no results on TCLP studies with vanadium-loaded GEH are available yet, we can only be guided by the disposal of arsenic-containing adsorbents.

As mentioned in an US-EPA study, exhausted adsorbents from drinking water typically pass the TCLP tests for arsenic, that is, <5 mg/L As in leachate (Sorg, 2008). Therefore, it can be assumed that vanadium-loaded adsorbents would show similar leaching behavior and could be classified as nonhazardous waste.

### 6 SUMMARY AND OUTLOOK

The extended efficiency test (EET) at the water work of Daun demonstrated that granular ferric hydroxide (GEH®) is an effective adsorption material for removing vanadium in drinking water and it is a simple and operationally safe process.

The GEH® plant achieved a specific treatment capacity of about 30,000 BV for an effluent concentration below 4 μg/L, an adequate performance for the given raw water conditions (with 30 μg/L V) with elevated concentrations of phosphate and silica, known to compete with vanadium.

The new water works at Kirchweiler will be finished by 2021, providing 12,500 inhabitants in the community of Daun with vanadium below the regulatory level. The planned treatment will include three parallel GEH®-adsorption filters with a total filling of 17 tons of GEH®. The regional government supports construction of this new treatment step with 645,000 Euros.

GEH® is now included in the provisional list of new treatment materials for Germany since December 2020 for a general phase of full-scale applications. Water suppliers with elevated vanadium levels may use this effective and certified treatment process. The results are translatable to other countries with similar vanadium occurrence and water characteristics in drinking water supplies and can be used for identifying the best available technology (BAT) for this metal.

Given that this paper is based on only one water source, further work on other sources embodying a range of water quality conditions would help elucidate a more general applicability for use of granular ferric hydroxide for vanadium as vanadate adsorption.

### CONFLICT OF INTEREST

It is noted that Carsten Bahr is employed by the company GEH Wasserchemie GmbH & Co. KG, which is the producer and supplier of the adsorbent Granular Ferric Hydroxide GEH® mentioned in this publication. The results presented in this publication were obtained as part of the extended efficiency test (EET) for approval of the product in Germany. The cost of this EET was covered by both the company GEH Wasserchemie GmbH &
Co KG and the local public water supplier, who will apply this treatment technology in future.

AUTHOR CONTRIBUTIONS
Carsten Bahr: Investigation. Martin Jekel: Investigation. Gary Amy: Investigation.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Gary Amy https://orcid.org/0000-0001-7591-5342

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