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TECHNICAL NOTE

Can wells in the vadose zone be backflushed to regain infiltration capacity? Concept and laboratory test

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Abstract

Vadose zone wells (VZW), or drywells, allow for high infiltration rates combined with small area demand. Nevertheless, they are rarely used for managed aquifer recharge, since turbid water leads to gradual clogging and a reduction in infiltration capacity. Established redevelopment measures require backflushing, which is commonly considered impossible for VZWs, making them "non regenerable". In this study, the possibility of backflushing a VZW is discussed. Key to the underlying approach is isolating the lower (clogged) section of a well and saturating its surrounding with water by infiltration via the upper (unclogged) screen. Subsequently, underpressure sucks water from the surrounding soil into the isolated section. The approach was tested with and without a gravel pack, on laboratory scale, showing a successful reversal of flow direction in both cases. The degree of redevelopment was quantified by measuring the drainage time of the well, which increased from initially 45 s without gravel pack and 40 s with gravel pack to 9,500 and 11,000 s, respectively, after clogging. After backflushing, the well with gravel pack showed a median drainage time of 95 s, which remained stable over ten cycles of clogging and backflushing. In contrast, drainage time of the well without gravel pack increased continuously to >170 s, even after vibrator application. In conclusion, it can be stated that the backflush of a VZW with the presented approach is possible and has an effect on the well's infiltration capacity, though it seems more effective for wells with gravel pack.

Keywords Artificial recharge · Unsaturated zone · Injection wells · Clogging · Well redevelopment

Introduction

As the demand for clean water is rising, the use of managed aquifer recharge (MAR) is gaining in popularity as a cheap and sustainable measure for water storage (Dillon 2005; Gao et al. 2014; Stefan et al. 2020). MAR is used to buffer seasonal water shortages/excesses of surface or runoff water (Henao Casas et al. 2021; Casanova et al. 2016), for additional treatment of wastewater that is to be reused (Icekson-Tal et al. 2003; Sharma and Kennedy 2017) or used for other purposes, and as the mitigation of problems connected to saltwater intrusion (Ebeling et al. 2019).

Managed aquifer recharge can be performed in many different ways. Most commonly, the water infiltrates the aquifer via infiltration basins or trenches, as they are cheap and easy to operate (Bouwer 2002). Another option is the use of infiltration or injection wells. These are widely used and require less space, but require more caution with operation and maintenance as they are prone to clogging when the water is not properly pretreated (Olsthoorn 1982; Jeong et al. 2018), since the hydraulic loading per area via wells is much larger than during basin infiltration.

Extent and dynamics of well clogging depend very much on water quality and well setup. Turbid water causes an accumulation of particles at the screen and in the gravel pack, where the clogging velocity depends mostly on the concentration of total suspended solids (TSS). Furthermore, the diameter and the installation of a gravel pack have a significant effect on the clogging dynamics (Jeong et al. 2018; Kalwa et al. 2021).

Usually, the screened portion of a well is situated in the saturated zone, as the well can then be used as a combined infiltration and pumping well, which is commonly referred to

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as aquifer storage and recovery (ASR; Pyne 2005). Pumping in infiltration wells, however, is not only conducted for the purpose of water abstraction, but it is also done to remove clogging layers and to reestablish infiltration capacity. This so-called "backflush" of a well represents the basis for the application of other, more advanced well-cleaning measures, such as brushing, acidification or ultrasonic stimulation (Fernandez-Escalante 2014; Houben and Treskatis 2007).

Bichara (1988) experimentally assessed different surging methods for the redevelopment of a physically clogged well and determined that the backflushing only had an impact on the well's hydraulic conductivity in the first seconds of pumping. Longer pumping times of up to 12 h had no additional benefits. Multiple reversals of flow, however, proved to be highly efficient and allowed a reestablishment of >70% of the initial hydraulic conductivity.

Very often, a well is meant to be screened in the vadose zone only and is then considered a "vadose zone well" (VZW) or "drywell" (see Fig. 1), an option for sites with a very pronounced depth to water, making it costly to drill down to the saturated zone (Edwards et al. 2016). Another reason for the installation of a VZW is the biodegradation potential in the vadose zone. As the interface area between the gas phase and the liquid phase is increased tremendously in the pores, so is the exchange of oxygen between soil air and soil water. This ensures aerobic conditions for the biocenosis, subsequently degrading many organic pollutants (Elkayam et al. 2015). In both cases, VZWs can add great benefits to MAR for the purposes of stormwater (Henao-Casas et al. 2021) and urban water management (Boroomandnia et al. 2021). In some countries, all kinds of MAR measures are restricted to the vadose zone if the water is not extensively pretreated before injection into the groundwater. One example is Germany, where the commonly applied guideline for rainwater infiltration (DWA 2005) does not allow a direct injection into the saturated zone. Instead, a minimum distance of 1–1.5 m between the well bottom and the average water table is mandatory.

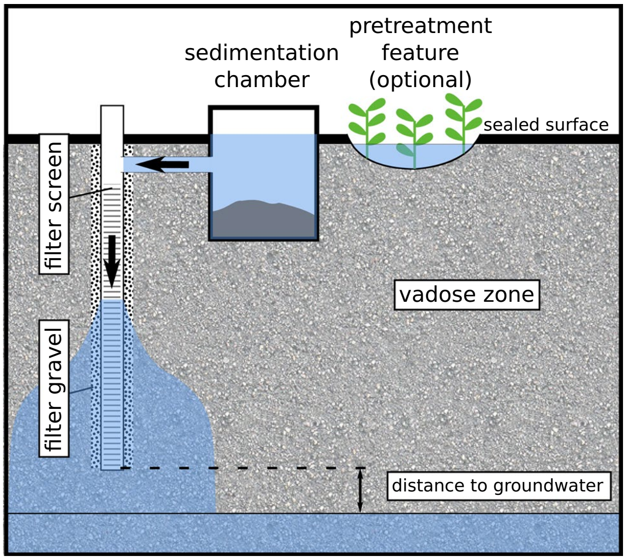

Fig. 1 The design of a typical vadose zone well (VZW)/drywell (after Edwards et al. 2016)

According to Bouwer (2002), "the main problem with VZWs is the impossibility of remediating […] clogging by pumping or redeveloping the vadose-zone well, because the well is in the vadose zone and groundwater cannot flow into it […] and "backwash" the clogging material". El Arabi (2012) and Jeong et al. (2018) came to the same conclusion. Consequently, clogging continuously diminishes the infiltration rate over time, until the well is clogged completely and has to be dismantled and rebuilt (Sasidharan et al. 2018; EPA 1999), although this only refers to VZWs constructed in porous aquifer systems. Karstic or fractured rock systems are considered potentially less affected by clogging (Edwards et al. 2016), but lack significant advantages of drywells in porous media with regard to retention and aeration in the vadose zone (Pronk et al. 2009); hence, the solution discussed here refers solely to VZWs set in porous media.

The literature covers different aspects of clogging prevention by pretreatment or siting of drywells/VZWs (EPA 1999) or of the clogging dynamics (Bichara 1986; Jeong et al. 2018; Kalwa et al. 2021) and the backflush and rehabilitation of wells in the saturated zone (Bichara 1988; Houben and Treskatis 2007). Backflushing and rehabilitation of VZWs, however, have not as yet been documented.

The option to backflush a well in the vadose zone, possibly in combination with other regeneration methods, would allow for more flexible and sustainable use of VZWs in the scope of MAR and stormwater management. In this technical note, a concept for the backflushing of VZWs is presented, which may appear trivial to some eyes but, to the best of the author's knowledge, has never before been documented nor discussed in the literature. Furthermore, the application of the method on a laboratory tank is depicted, proving its hydraulic functionality as well as the redevelopment effectiveness on a laboratory scale.

Concept for backflushing

In order to reverse the flow direction and free the pores in the well's surrounding from obstructive particles, two conditions are required:

1. The surrounding soil is (nearly) saturated with water
2. A negative pressure gradient from the soil to the well is established

The first condition can be achieved by isolating a section inside the well and infiltrating water above. Due to gravitational forces, the infiltrating water will flow vertically to the surrounding of the lower screen parts and the capillary forces of the pores will retain some of the water and increase the water content here. Two factors are decisive for the water saturation here:

1. *Infiltration rate via the upper screen section.* The higher the infiltration rate via the upper screen section, the higher the saturation at the lower screen section (demonstrated in various numerical studies, e.g. Sasidharan et al. (2019).
2. *Soil texture.* Infiltration wells are usually screened in the more permeable section of a soil profile, consisting of gravel and sand. The coarser the sediment here, the weaker the capillary forces and the lower the water content in this situation (Radcliffe and Šimůnek 2010; Richards 1931).

If the infiltration rate is high enough, and the lithological conditions are favorable (medium sandy soil), the surrounding of the clogged screen section will show a high saturation and the pore pressure can be assumed to be close to atmospheric pressure (10.1 hPa) or even higher (van Genuchten 1980). Thus, an underpressure can be applied inside the isolated well section to achieve the second condition and cause the water to flow from the surrounding soil into the well via the clogged screen section.

Many of the aforementioned aspects have already been discussed in the scope of soil water sampling (Grossmann and Udluft 1991; Weihermüller et al. 2007). However, the purpose and scale of the solutions discussed there differ substantially from the problem addressed here; furthermore, they are usually designed to extract a representative portion of the water in the unsaturated pores, i.e. without disturbing the hydraulic conditions too much. In contrast, the solution here tries to explicitly increase the soil's saturation and create high flow velocities towards the VZW without focusing on the actual origin and nature of the extracted water.

It is expected that the lower parts of a well are more prone to clogging than the upper ones, due to the fact that the upper part is not always flooded. Furthermore, the Glover solution (Zangar 1953) and other modeling approaches for flow from a VZW (e.g. Elrick and Reynolds 1992) predict a higher flow velocity for the lower parts of the screen than for the higher ones, due to the larger pressure gradients. As a higher hydraulic loading per area increases the velocity for physical clogging (Kalwa et al. 2021; Perez-Paricio 2001), the lower sections are expected to clog earlier and show a much smaller hydraulic conductivity than the upper parts.

In order to mobilize flow-inhibiting particles at the clogged screen section, the flow velocity during the backflush is a decisive factor (Hartwig et al. 2013). In order to mobilize particles of 10–20 µm, a minimum flow velocity of approximately 2–3 cm/s is required (Houben and Treskatis 2007). Achieving such a high flow velocity in the well's surrounding requires a high-pressure gradient between the saturated pores and the well, which can only be achieved by applying an extremely strong vacuum pump. Alternatively, the high-pressure gradient can be applied for a short moment in time by using a buffer—e.g. a storage tank with underpressure is connected abruptly to the isolated section of the well. In this moment, the VZW is emptied of air and the underpressure is applied instantaneously to the well–aquifer interface. Since Bichara (1988) has shown that the main redevelopment effect at a well is achieved in the first seconds of the backflush, it is assumed that this short application will have a significant impact, especially if repeated several times.

The suggested backflushing procedure, requiring complete prevention of vertical flow inside the well or the gravel pack, is displayed in Fig. 2. Thus, the VZW should either be installed without a gravel pack, which would lead to a significantly increased clogging rate (Kalwa et al. 2021), or with vertical flow barriers spaced at regular intervals inside the gravel pack. The approach suggested here requires two pneumatic packers, a storage tank, a vacuum pump, two valves and connecting hoses.

In order to redevelop a clogged section of the well, it is isolated with the packers. Then, freshwater is infiltrated, ponding on top of the upper packer. When the well's surrounding is assumed to be saturated well enough, an underpressure is established in the storage tank. Subsequently, the tank is isolated from the vacuum pump (to protect it from damage) and the valve between the isolated well section and the storage tank is opened abruptly. The water is then sucked into the well, flushing the particles from the well's surrounding into the well and from there into the storage tank. Finally, the storage tank is emptied and the procedure can be repeated. The approach allows the application of additional regeneration techniques, such as pulse methods and/or chemical regeneration methods, if they are adapted to the conditions in the vadose zone.

Vadose zone wells are often constructed with a large diameter (d) of >0.5 m and are sometimes filled with gravel (Edwards et al. 2016; Chen et al. 2008; Sasidharan et al. 2018). These wells are difficult to adapt to the method suggested here, which is instead meant to be used for smaller wells ($d = 0.06$–0.2 m) that clog faster (Kalwa et al. 2021), but are much cheaper in construction and can be adapted by intercalating the gravel pack with vertical flow barriers.

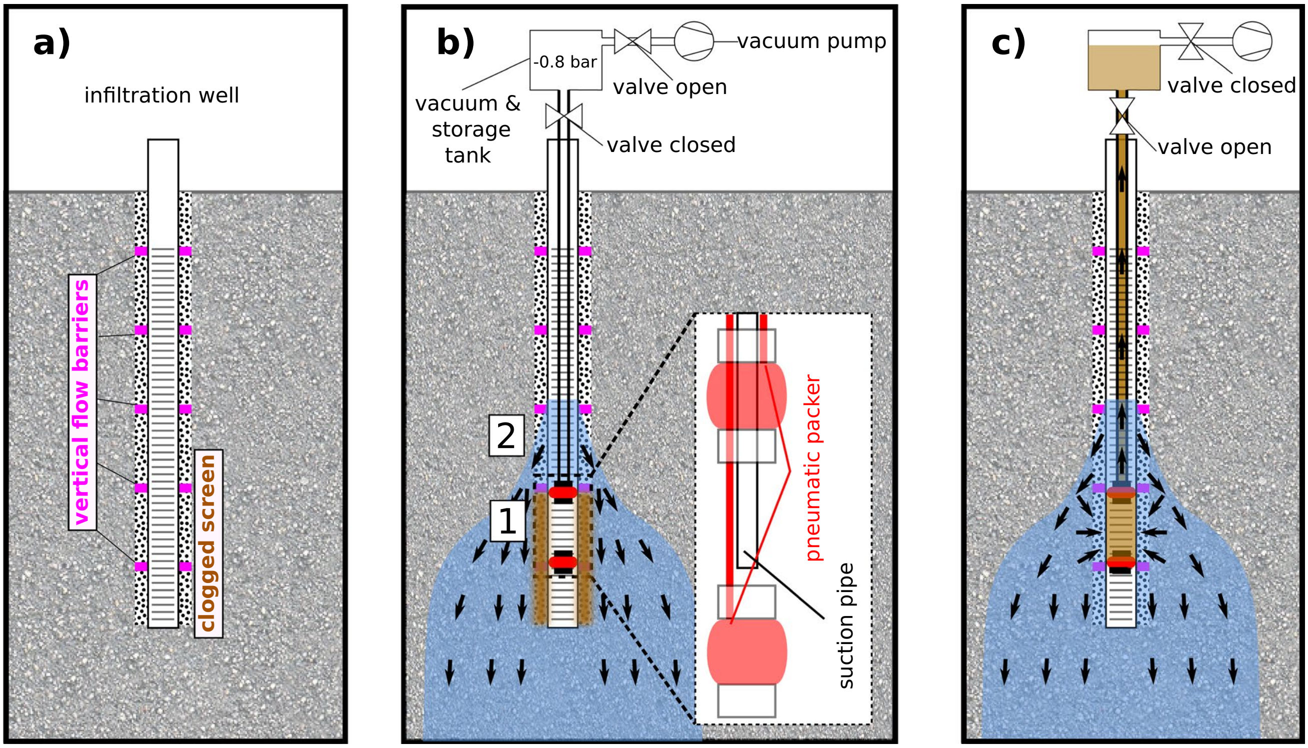

Fig. 2 Concept for backflush: **a** A VZW with vertical flow barriers, installed in the filter gravel, where the lower parts of the screen are blocked. **b** Phase I of redevelopment: a part of the clogged screen is isolated with pneumatic packers (Bergant et al. 2006) and water is infiltrated via the screen above (Bichara 1986), saturating the soil surrounding the clogged screen. The vacuum pump generates negative pressure in the storage tank. **c** The valve between the isolated well volume and the storage tank is opened and the water is sucked into the well from the surrounding soil, backwashing the clogged screen and flushing the particles in suspension into the storage tank

Materials and methods

Experimental setup

The approach was tested in a sandbox with an area of 6 m^2 and a height of 1.25 m. The upper 0.9 m consisted of medium sand with a saturated hydraulic conductivity of $K = 2 \times 10^{-4}$ m/s. The van Genuchten parameters of the sand were determined with the HYPROP method and by inverse modeling with Hydrus2D as $\alpha = 0.16$ cm^{-1} and $n = 2.7$, indicating rather weak capillary forces in the sediment. The lower 0.35 m of the box was filled with a drainage layer of gravel ($K \approx 1 \times 10^{-2}$ m/s). To minimize ponding, a perforated tube was installed inside the gravel layer, draining the water from the tank (see Fig. 3).

To test the approach for a well without a gravel pack, a PVC well screen (inner/outer diameter: 50/60 mm; slot size: 0.2 mm; approximate open screen area: 5%) was installed to a depth of 0.7 m below the sand surface, leaving 0.2 m of vadose zone to the gravel layer and the water table. This setup was also used to test the application of additional mechanical regeneration measures, by attaching a small HDPE pipe next to the screen pipe, allowing the insertion of a pulse generator to any depth desired. For this purpose, a concrete vibrator (Makita DVR450) was used with a net weight of 3.5 kg, 13,000 rpm and an amplitude of 1.0 mm.

In order to test the approach on a well with gravel pack, the same well screen was surrounded by a gravel layer with a thickness of 2.5 cm, resulting in a total borehole diameter of 11 cm. At 0.2 m above the well bottom, a vertical flow barrier with a thickness of 1 cm, made of PVC, was installed inside the gravel pack. For this setup, no additional pipe was installed and the vibrator was not applied, as it proved difficult to combine this with the gravel pack itself. For isolating the lower from the upper screen section inside the well, a pneumatic packer (10 cm long) was used, which was connected to a 5-L storage tank and the vacuum pump.

Experimental procedure

Each clogging-backflush cycle was started by clogging the lower 20 cm of the well screen with a bentonite suspension (200 mg/L, resulting in a turbidity of approx. 70 FNU). In order to not exceed this water level, the initial infiltration rate (~40 ml/s for the well without gravel pack and 60 ml/s for the well with gravel pack) had to be continuously decreased throughout the clogging process. The pump was

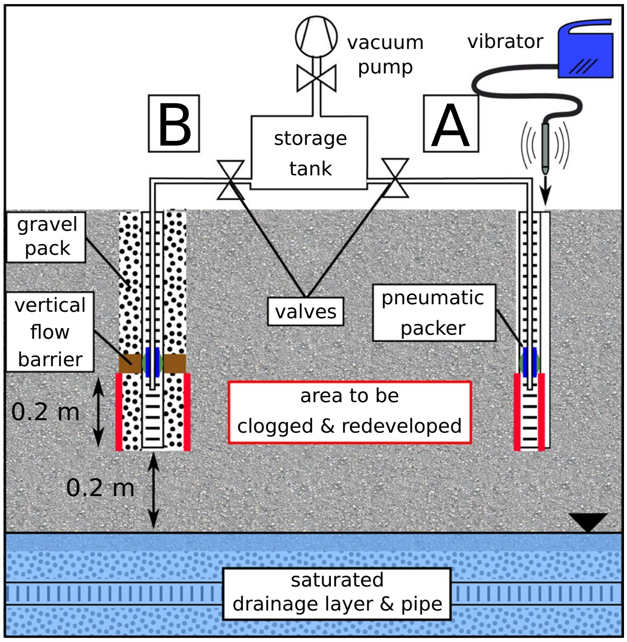

Fig. 3 Experimental setup: the approach was tested, using a pneumatic packer on two physical well models. One with a diameter of 60 mm without a gravel pack and a 1″-pipe (2.54 cm) attached to introduce the vibrator (setup A), one with a gravel pack (diameter $d = 110$ mm), where a PVC foil was installed as a vertical flow barrier at 0.2 m above the well bottom (setup B)

stopped, when the pumping rate was 100 times lower than before the first cycle, i.e. 0.4 and 0.6 ml/s, respectively. As the Glover equation (Zangar 1953) indicates that infiltration rate and hydraulic conductivity are connected in inverse proportion, the K of the well's surrounding was assumed to have dropped by approximately two magnitudes (thus, $K \approx 2 \times 10^{-6}$ m/s).

The inserted water volume and bentonite mass were determined and a falling-head infiltration test was conducted, determining the time until the well was drained completely. Afterwards, the backflush was conducted by inserting the packer into the well and isolating the clogged area. Then, a constant volumetric flow of water (approx. 70 ml/s) was established into the upper part of the well to saturate the well's surrounding. After 60 min of inflow, the well's surrounding was considered to be saturated and the backflush was started. For this, an underpressure of $p = -0.8$ bar was established in the storage tank and the valve to the vacuum pump was closed. Then, the valve leading to the passage was opened, transferring the underpressure abruptly to the isolated well space, sucking water from the partly saturated soil into the well and from there into the storage tank until the underpressure had dissipated completely. Subsequently, the tank was emptied and the procedure was repeated, until the turbidity in the regained water fell below 20 FNU (≈ 0.05 g/L suspended bentonite), which usually required 5–10 repetitions. Then, the pneumatic packer was removed and the drainage time was determined again.

For the well without gravel pack, six cycles were conducted without additional measures. As the backflush efficiency appeared to be declining after this time, the vibrator was applied in addition to the backflush for the cycles 7–10. For the well with gravel pack, ten clogging-backflush cycles were conducted without applying the vibrator.

Results and discussion

Infiltration capacity/drainage time

No gravel pack

The drainage times before and after the backflush are displayed in Fig. 4. The initial drainage time was 45 s. After the clogging, the drainage time was extended to 9,500 s (median of all ten cycles), whereas after the backflush, it was shortened to a median value of 109 s (240% of the initial value). Over time, however, the well showed a subsequent rise in drainage time to more than 170 s after the 6th cycle (>380% of the initial value), which was seen as a sign of the unsustainability of the redevelopment and a declining efficiency of the backflush with every cycle.

At this point, the vibrator was applied, which apparently helped to shorten the drainage time again to less than 100 s. Although it was then applied in every following cycle, again, a subsequently increasing drainage time was observed, reaching 180 s after the 10th cycle; thus, even the combination of backflush and vibrator application had a declining efficiency for the well's redevelopment.

Gravel pack

The initial drainage time was 40 s. After clogging, the well required 11,000 s (median) for draining, which was reduced to a median value of 95 s (≈ 230% of initial value) after the backflush. The infiltration capacity did not show any significant trend in time neither before nor after the backflush, indicating that the redevelopment efficiency was similar after the first and the 10th cycle.

Turbidity observations

No gravel pack

The amounts of inserted and extracted suspended solids are depicted in Fig. 5. The median amount of inserted bentonite mass was 0.8 g, after ten cycles a total of 10.3 g had been given into the well. Over time, the inserted mass for each cycle remained between 0.6 and 2.4 g before the

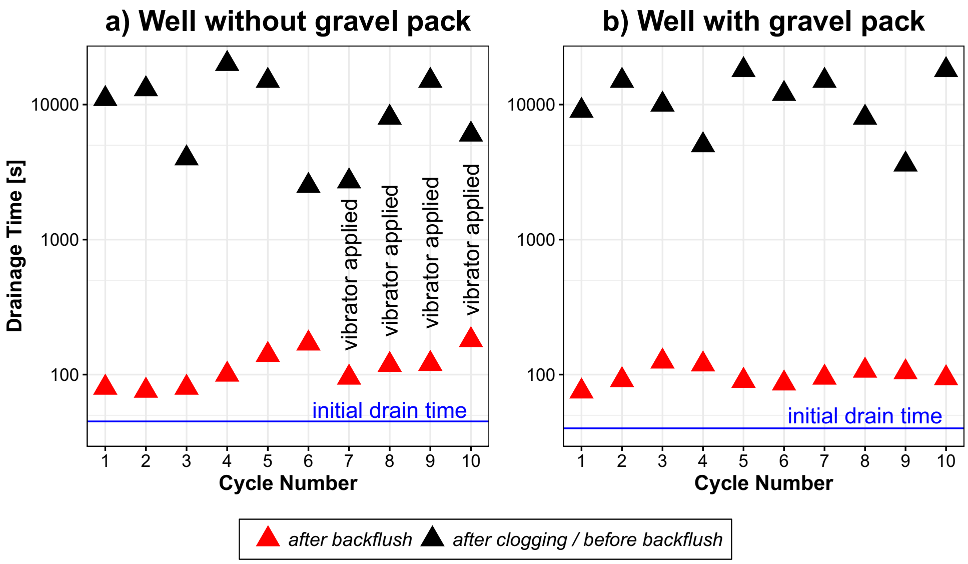

Fig. 4 Drainage times after clogging and after the backflush for each cycle. The initial drain time (before first clogging) is depicted with the blue line. **a** After clogging, drainage times varied between 2,700 and 20,000 s. After the backflush, the well without gravel pack showed increasing drainage times over the first six cycles from 80 to 170 s. During cycle 7, the vibrator application in parallel to the backflush caused a reduction to 95 s. In the following cycles, however, repeated vibrator applications did not have the same effect, and drainage times started increasing again to 180 s in cycle 10. **b** No similar trend was observed and drainage times after the backflush varied between 75 and 125 s (arithmetic mean: 99 s), whereas after clogging, they varied between 3,600 and 18,000 s

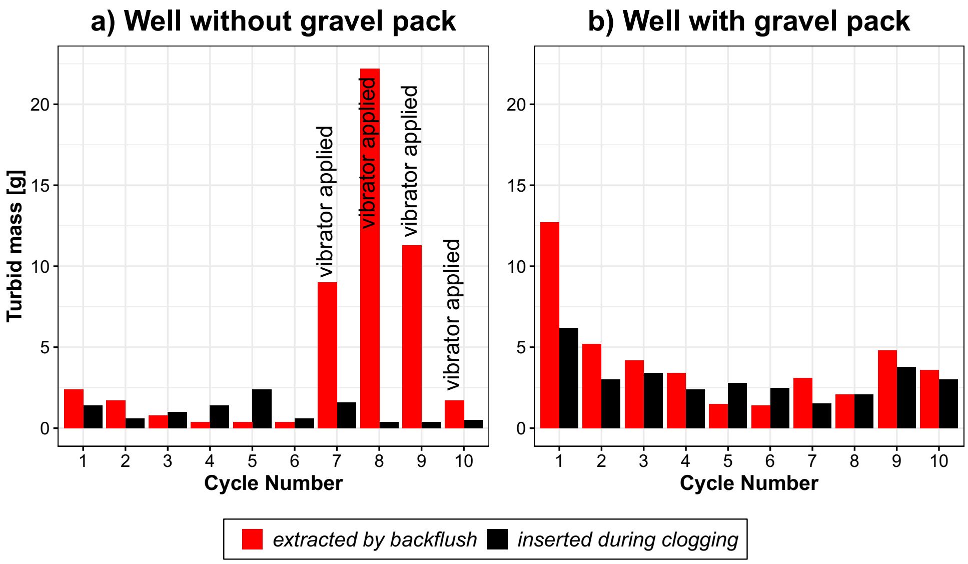

Fig. 5 Inserted and extracted mass of suspended solids. **a** Well without gravel pack: The inserted turbid mass varied between 0.4 and 2.4 g per clogging cycle, whereas the extracted mass decreased from 2.4 to 0.4 g for each backflush after the first six cycles, extracting less turbid mass than had been inserted. After application of the vibrator, a sudden increase to 9 and 22 g of extracted mass was observed. In cycle 10, however, the extracted mass had decreased to previbrator levels again (1.7 g). **b** Well with gravel pack: In total, more mass was extracted than inserted. An overall decrease in extracted mass from 12.7 to 1.4 g after five cycles and a rather erratic variation between 2.1 and 4.8 g in the aftermath (without vibrator application) can be seen. The inserted mass did not show any trend and varied between 6.2 and 1.5 g per clogging cycle

first application of the vibrator. After the introduction of the vibrator in cycle 7, however, the inserted mass dropped constantly below 0.5 g, indicating that the regenerated well clogged much faster than before. This could have been due to a higher compaction, caused by the vibrator's pulses or to fine particles, accumulating deeper inside the sediment.

The extracted mass of suspended solids showed a decreasing trend at first from 2.5 to 0.5 g. With application of the vibrator, however, more than 22.5 g (much more than introduced by clogging before) were extracted during the following three cycles. These particles most probably derived from the sediment itself, which was not washed before installation, possibly containing low amounts of silt and clay particles. In the last cycle, however, the extracted mass fell back to 1.7 g.

Gravel pack

As expected, the gravel-equipped well required a higher amount of suspended solids to reach the “clogged state” (median: 2.9 g; cumulated input after 10 cycles: 30.8 g). Only the first cycle shows exceptionally high input and output of suspended solids The inserted mass showed a slightly decreasing trend in the beginning, which apparently stabilized after seven cycles. The mass of extracted solids hardly deviated from the inserted mass, except for the first cycle, indicating that most of the inserted fines were extracted by the backflush and that this redevelopment was conducted with a similar efficiency over all ten cycles.

Conclusions and outlook

The backflush approach proved to be functional for VZWs on a laboratory scale. A sustainable redevelopment of infiltration capacity, however, was only possible for the well with gravel pack. Even though after ten clogging-backflush cycles, the well did not show the same infiltration capacity as initially, the drainage time was sustainably kept around 230% of the initial value after the backflush. The well without gravel pack showed a continuously worsening performance with drainage times increasing to >380% of the initial value, which was only partly compensated for by applying the vibrator, indicating an accumulation of a certain amount of flow-inhibiting particles in the near well surrounding, which could not be removed by the backflush. All of these observations are consistent with the literature on the regeneration of saturated zone wells (Bichara 1988; Houben and Treskatis 2007).

In this study, only physical clogging has been considered. As biological or chemical clogging processes differ strongly and might require additional redevelopment measures (such as acidification), the efficiency of the approach on wells clogged in this way is still to be proven.

Due to the Covid-19 pandemic situation, tests could only be conducted in the laboratory; thus, many practical aspects of full-scale wells remain untouched, including the role of the lithology surrounding the well.

The approach was only tested for its applicability in homogeneous medium sand. Coarse sand or gravel, however, might not retain enough water for the backflush, whereas the low hydraulic conductivity of fine or loamy sand could limit the flow rate to the well and thus, the backflush efficiency. It is still to be determined whether the approach will be similarly efficient for the other types of sediments as well.

Furthermore, a heterogeneous sediment would change preferential pathways for water flows. It can be assumed that impermeable horizontal layers would result in an inhibition of vertical flow, and hence a better saturation of the well’s surrounding, which would rather facilitate the application of the method. Regarding varying permeability along the filter section, the most permeable sections are assumed to clog first and would also be activated first during regeneration. However, to test these hypotheses, a field-scale study is required. A more elaborated laboratory study, including the monitoring of hydraulic capacity and a real-time water and solid balance, would allow the setup of a flow and transport model to better understand the processes during regeneration. Due to high-pressure gradients, however, nonlaminar flow can be suspected at the well, which complicates the use of common Richards-based models for the vadose zone, such as Hydrus2D/3D (Sasidharan et al. 2019).

For deeper wells, the setup might have to be adapted. Here, the vertical transport from the isolated well section to the storage tank could pose a problem. If the tank is situated on the ground surface and the well is deeper than 7 m, cavitation will prevent the water from flowing into the tank. Furthermore, every meter of vertical transport distance weakens the effective underpressure, applied to the screen, possibly affecting the backflush efficiency. In order to avoid this, there are three possibilities:

1. Introducing the vacuum tank into the well. This, however, would limit the volume of the tank substantially.
2. Introducing an immersion pump into the isolated well section. The pump could be activated after the well section is filled with water from the pores, as shown in Fig. 6.
3. Alternatively, the isolated well section could also be filled with water from the surface (not by sucking water from the soil matrix into the well) and the immersion pump could then be activated. In this case, however, the abrupt pressure change, supposedly causing a hydraulic shock equivalent to the so-called “water hammer” (Bergant et al. 2006), is not applied to the well screen and its surrounding.

Nevertheless, if the results from this study turn out to be generalizable, VZWs could be made easily redevelopable, by installing vertical flow barriers in the surrounding gravel pack. These wells could then be applied for urban water

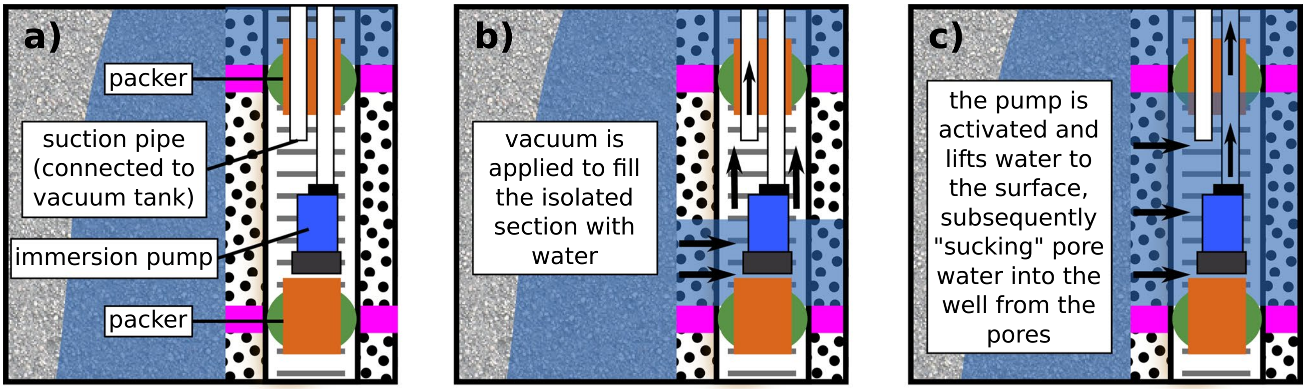

Fig. 6 Combination of vacuum tank and immersion pump to backflush the well in the vadose zone: In order to fill the empty well (**a**) with water, an underpressure is applied to the isolated well section (**b**). As soon as the pump is inundated, it can be activated to transfer the water to the surface (**c**)

management to infiltrate low-quality waters with minimal area demand, despite a certain risk of clogging.

Surface sealing in urban areas poses an increasing hydrological problem (Scalenghe and Marsan 2009). Runoff from these areas could be significantly decreased, and groundwater recharge increased, if space-saving infiltration solutions such as VZWs became an applicable tool in this context. They open new possibilities for MAR under land constraints, e.g. if the depth-to-water is too pronounced for drilling wells into the saturated zone or if direct injection into the groundwater is restricted by law.

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Declarations

Conflicts of Interest The author declares no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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