Abstract: The decentralized treatment of wastewater and its on-site infiltration is common practice, especially in rural areas. However, uncertainties exist on the degradation potential of treated wastewater constituents mixed with additional infiltration of large quantities of water originating from precipitation. The intermixture of these waters is causing a reduction of residence times of the treated wastewater as well as an increased water saturation within the unsaturated soil zone. This can lead to a negative influence on the purification efficiency. Laboratory-scale 1D column experiments, accompanied by numerical simulations of water flow using the software code HYDRUS 1D, have been performed to evaluate the risks for a reduction of the degradation efficiency. Water content measurements and analysis of relevant organic substances in samples taken at different depths were the basis for evaluating the influence of the joint infiltration on the purification efficiency. The results highlight that a joint infiltration of treated wastewater and additional water originating from precipitation is not affecting the degradation efficiency for treated wastewater constituents. Degradation rates under these conditions were similar to the infiltration of treated wastewater alone. Timeframes with high water saturation were limited to the duration of the precipitation event.

Keywords: column experiments; treated wastewater infiltration; precipitation; degradation efficiency; unsaturated soil zone; numerical modeling

1. Introduction

Only about 86% of households are connected to the central public wastewater treatment system in the Free State of Saxony, Germany [1]. In sparsely populated regions, especially with small municipalities or stand-alone residential and leisure facilities, a centralized wastewater treatment plant is not always available or the connection through, e.g., pipes is uneconomic and/or technically not realizable. In general, the connection to a central system often comes with high expenses for the installation of pipeline networks. Furthermore, the constant energy and maintenance costs of necessary pumping stations are a critical aspect [2–7].

Small wastewater treatment plants (SWWTP) represent an alternative, economic method for the on-site treatment of wastewater in these regions. According to German DIN standard [8], SWWTPs are defined as systems for the treatment of wastewater from domestic use up to a volume of 8 m³ per day, which is roughly the amount of wastewater produced by about 50 residents. After treated wastewater leaves the SWWTP, it is normally discharged into a river or stream. The acceptable maximum contaminant levels (MCLs) for specific dissolved constituents, such as chemical oxygen
demand (COD) and biological oxygen demand (BOD) are defined in [9]. However, especially in rural regions, a sewer system is not available, nor is the discharge into receiving waters possible. In these cases, the disposal of the treated wastewater effluent (TWWE) takes place by direct infiltration into the soil by means of infiltration elements such as soakaways, trenches, drainage pipes, or swales [8]. As a result, direct infiltration into the ground contributes to controlling the sustainable recharge of an aquifer and attempts to maintain a constant groundwater level. Regarding climate change, this has particular importance to overcome frequent and significantly longer dry periods, which can be expected in the future [10–12].

However, for the disposal of TWWE by direct infiltration into the soil system, the aspects of subsurface purification and groundwater pollution risk have to be taken into account, especially with regard to European Commission Directive [13]. It is specified that all member states must achieve a good chemical and ecological status of all waterbodies. In particular, this includes reduction of dangerous substances released into groundwater, protection and improvement of the current state of aquatic ecosystems, and promotion of sustainable use of the groundwater resources. In order to meet the EU Water Framework Directive [13], the infiltration of TWWE must be feasible for both present and future climatic and hydrogeological conditions. Numerous field and laboratory studies indicate that several organic compounds, such as nitrogen, phosphorus, bacteria, and viruses, within the TWWE can be removed substantially by percolating them through the unsaturated soil zone [14–17].

However, this removal process can be influenced by irregular and additional infiltrations originating from intensive precipitation events at the locations of installed TWWE infiltration systems. At a pilot site in Schöneck, Germany, this influence was observed at an SWWTP followed by on-site infiltration of TWWE through subsurface ditches. Due to large quantities of water originating from intensive precipitation events, flooding occurred in the installed ditches. A temporary impact on the hydraulic conditions in the unsaturated soil zone was apparent due to observed water contents close to saturation [18]. As a result, risks and uncertainties arise about the degradation of residues contained in the TWWE, the hydraulics of the unsaturated soil zone, and the overall pollution of groundwater resources. To assess potential groundwater contamination, it is necessary to evaluate the advective and reactive transport processes as well as their interaction in the unsaturated soil zone below the infiltration system. On the one hand, these processes are influenced by site-specific parameters, such as soil matrix, which has impacts on the distribution, retention, and residence time of the infiltrating TWWE and additional water. On the other hand, the processes are influenced by operational parameters of the system such as infiltration rates or the infiltration cycle [19,20].

Soil column experiments were performed to assess the hydraulic influence on the infiltration of TWWE in combination with the simultaneous occurrence of water originating from intensive precipitation events. The main focus was to evaluate the spatiotemporal variation of water saturation and degradation potential for TWWE constituents in the subsurface zone. The column experiments are supported by numerical studies using software code HYDRUS 1D [21] to verify the observations of water flow behavior in the laboratory tests.

The knowledge obtained from the investigations should finally allow making statements on the risk of the reduction of the purification efficiency in the unsaturated soil zone at sites with joint infiltration of TWWE and additional water from precipitation events.

2. Materials and Methods

2.1. Column Experiments-Set Up

To address the aim of the study, four 1D acrylic glass columns (160 cm long, diameter 15 cm) (Figure 1) were constructed. Glass beads (1 to 2 mm) were placed to a height of 8 cm at the column bottom to avoid washing out of finer sand grains above. Each of the columns was packed with different types of sandy soils to a total height of 140 cm, representing materials suitable for infiltration according to German DIN standard [8].
Figure 1. Set-up of 1D-column experiment.

The initial parameters describing the soil material were obtained from permeameter tests [22] and retention behavior experiments [23] by taking soil samples from each column (Table 1).

Table 1. Initial parameters obtained from the permeameter test [22]; bulk density estimated by [24] and retention behavior laboratory test [23].

| Parameter                                              | Soil 1 | Soil 2 | Soil 3 | Soil 4 | Glass Beads |
|--------------------------------------------------------|--------|--------|--------|--------|-------------|
| Hydraulic Conductivity under full saturation (cm day⁻¹) | 478    | 363    | 4234   | 2333   | 15,456      |
| Bulk density (g cm⁻³)                                  | 1.68   | 1.70   | 1.67   | 1.65   | 1.52        |
| Content of sand (%)                                    | 99.6   | 92.5   | 100    | 100    | -           |
| Content of silt (%)                                    | 0.4    | 7.1    | 0.0    | 0.0    | -           |
| Content of clay (%)                                    | 0.0    | 0.4    | 0.0    | 0.0    | -           |
| Van Genuchten shape parameter α (cm⁻¹)                 | 0.046  | 0.027  | 0.053  | 0.047  | 0.031       |
| Van Genuchten shape parameter n (-)                    | 4.08   | 4.26   | 3.93   | 2.96   | 5           |
| Residual water content θr (cm³ cm⁻³)                   | 0.084  | 0.094  | 0.072  | 0.069  | 0.036       |
| Saturated water content θs (cm³ cm⁻³)                  | 0.34   | 0.37   | 0.39   | 0.35   | 0.31        |
| Pore connectivity parameter in the conductivity function l (−) | -1.85  | -1.50  | -1.58  | -2     | unknown     |

For the estimation of spatial and temporal distribution of soil moisture, the experimental columns were equipped with Frequency Domain Reflectometry (FDR) probes (Co. Stevenswater, Portland, OR, USA) to measure water content in two different depths (Obs1-0.25 m and Obs2-1.15 m below surface) every 10 min. A soil-specific calibration using TWWE was performed to minimize the error from this source. Suction cups (Co. Rhizosphere, Wageningen, NLD) were installed in five different depths (0.15/0.45/0.75/1.05/1.35 m below soil surface) for direct extraction of pore water for chemical analysis.

The columns were placed in a climate chamber with a constant temperature of 10 °C in accordance with conditions (mean annual temperature 10–11 °C) in the lower layers of the unsaturated soil zone.
2.2. Column Experiments—Operation System

2.2.1. TWWE Infiltration

Only TWWE was infiltrated in the first experimental phase to simulate a typical operational mode of a standard on-site infiltration system. In addition, stable biodegradation was achieved prior to initiating the second experimental phase with joint infiltration of TWWE and additional water originating from precipitation. The amount of TWWE to be infiltrated per day was defined on the basis of the requirements of two German DIN standards [8,25]. There, it is specified that the daily TWWE of 150 L per population equivalent (PE), corresponding to the mean amount of domestic wastewater in rural areas, is to be infiltrated on a minimum area of 1 m$^2$. Based on a column surface area of 0.018 m$^2$, the amount of TWWE to be infiltrated per day was 2.62 L.

TWWE was intermittently applied according to the hydrograph of the daily water consumption [26] directly at the column top and therefore on the soil representing the first soil layer below the infiltration ditch (see Supplementary Materials S1). Thus, a realistic infiltration pattern with increased wastewater accumulation in the morning and evening hours of a day was realized. The average residence time of the TWWE in the soils, determined by tracer experiments, was 3.1 d (soil1), 3.15 d (soil2), 2.38 d (soil3), and 2.71 d (soil4).

The TWWE originated from an SWWTP with 50 residents and was collected every four weeks. The concentrations of the constituents varied in a significant range, depending mainly on the sampling date (Table 2). The TWWE was stored at a constant temperature of 10 °C to ensure stable composition.

| Type of Water | pH (-) | EC (µS cm$^{-1}$) | COD | NO$_2$-N | NO$_3$-N | NH$_4$-N | PO$_4$-P |
|---------------|-------|------------------|-----|----------|----------|----------|---------|
| TWWE          | 7.1 – 7.7 | 960 – 1080     | 49 – 120 | n.d. – 3.2 | 3 – 57    | 3 – 82    | 18 – 44  |
| PW            | 6.2    | 58                  | n.d. | n.d. | 2        | n.d.      | n.d.     |
| Limit value [27] | 6.5 – 9.5 | 2790             | n.a. | 0.15 | 11.3     | 0.39      | n.a.     |

Notes: n.d.—not detectable, n.a.—not available.

When assessing the shown TWWE concentrations, it becomes apparent that a potential amount of residual concentrations still remains (e.g., NH$_4$-N), which might have an impact on groundwater quality under certain circumstances (e.g., short distance to the aquifer, soils with high hydraulic conductivity). Therefore, the experiments were carried out to provide evidence of the degradation potentials of the residual concentration on the first 1.4 m of soil passage.

The occurrence of clogging, especially in soil 2, was observed during the experimental runtime. The accumulation of organic matter and suspended solids as well as the growth of biofilms in the upper soil layer led to a reduction of the infiltration capacity. The uppermost centimeter of the soil had to be replaced regularly by scraping the material.

2.2.2. Joint Infiltration of TWWE and Additional Water Originating from Precipitation

The second experimental phase simulated the joint infiltration of TWWE and additional water to investigate the influence of these events on the biocenosis and the purification efficiency. Additional water, in accordance with intensive precipitation events, was applied to the test columns. Different precipitation events, based on statistical recurrence interval of 5 years event (Table 3) (rated precipitation according to [28]) at Schöneck/Vogtland were simulated after achieving stable degradation of infiltrated residuals in the first experimental phase.
Table 3. Precipitation intensities of different event durations for an event of statistical recurrence interval of 5 years for the site Schöneck/Vogtland.

| Duration (min) | 5      | 10     | 15     | 20     | 30     | 45     | 60     | 90     | 120    |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Intensities (L s\(^{-1}\) ha\(^{-1}\)) | 322.9  | 245.1  | 201.4  | 172.5  | 136    | 105.5  | 87.4   | 64.2   | 51.6   |
| Duration (min) | 180    | 240    | 360    | 540    | 720    | 1080   | 1440   | 2880   | 4320   |
| Intensities (L s\(^{-1}\) ha\(^{-1}\)) | 38     | 30.6   | 22.5   | 16.6   | 13.4   | 10.5   | 8.8    | 5.5    | 4.2    |

Intensities of different precipitation event durations were acquired by using data from [29]. This dataset is based on measured values of precipitation for a period between 1951 and 2010 and is valid for different reference sites in Saxony, Germany.

Based on the hydraulic conductivities of the used soils 1, 3, and 4, a 5-year precipitation event had a length of 30 min and an intensity of 136 L s\(^{-1}\) ha\(^{-1}\) (Table 4, event 1). Due to the lower hydraulic conductivity, an event length of 120 min with an intensity of 51.6 L s\(^{-1}\) ha\(^{-1}\) was used for soil 2 (Table 4, event 1). This resulted in a loading rate per column surface area of 14.4 mL min\(^{-1}\) (column 1, 3, 4) and 5.5 mL min\(^{-1}\) (column 2). These amounts were infiltrated directly on the top soil layer, representing additional infiltration from precipitation. Subsequently, event durations and intensities were increased to simulate worst-case events (Table 4, events 2 and 3) for investigating the effects on the purification efficiency caused by higher water content, on the one hand, and longer periods with increased water content, on the other hand.

Table 4. Precipitation duration (min) and intensities as well as loading rate per soil surface area and total infiltrated volume for the 3 simulated events.

| Event | Duration (min) | Intensity (L s\(^{-1}\) ha\(^{-1}\)) | Loading Rate Per Column Surface Area (mL min\(^{-1}\)) | Total Infiltrated Volume Per Event (mL) |
|-------|----------------|------------------------------------|-----------------------------------------------------|---------------------------------------|
|       | Soil 1, 3, 4   | Soil 2                             | Soil 1, 3, 4                                        | Soil 1, 3, 4                          | Soil 1, 3, 4                          | Soil 2                             |
| 1 (5a) | 30             | 120                                | 136                                                  | 51.6                                  | 14.4                                  | 5.5                                 | 432                                 | 656                                 |
| 2 (Intensity * 5, Duration * 10) | 300           | 600                                | 680                                                  | 258                                   | 72.1                                  | 27.4                                | 21,630                              | 16,413                              |
| 3 (24 h) | 1440         | 1440                               | 136                                                  | 51.6                                  | 14.4                                  | 5.5                                 | 20,765                              | 7878                                |

The infiltrated synthetic precipitation prepared on the basis of demineralized water contained 6.86 mg L\(^{-1}\) NaNO\(_3\), 1.64 mg L\(^{-1}\) KHCO\(_3\), and 26.96 mg L\(^{-1}\) CaSO\(_4\). Corresponding concentrations of the most important quality parameters are shown in Table 2. Between two consecutive precipitation events, only TWWE was infiltrated for at least two weeks to provide sufficient time for the microorganism community to recover.

2.2.3. Sampling

To evaluate the degradation of TWWE constituents and to determine vertical concentration profiles, samples were collected once a week through five ports in each column. While simulating the precipitation events, sampling was carried out directly before the event and 24 h and/or 72 h after the event to investigate the influence of the precipitation events on the purification efficiency. However, the sampling procedure always needed a total period of 3 h starting from 9 a.m. until 12 p.m. on the specific days to get an equal amount of sample through five suction cups for successful chemical analysis.
2.3. Analytics

Quantitative analysis of the most important quality parameters chemical oxygen demand (COD), ammonium-nitrogen (NH$_4$-N), nitrate-nitrogen (NO$_3$-N), and phosphate-phosphorus (PO$_4$-P) in the pore water, extracted by installed suction cups, were carried out by spectrophotometric method. Measurements were performed while using UV-VIS spectrophotometer DR 6000 and associated Test Kits LCI 500 (COD), LCK 304 (NH$_4$-N), LCK 339 (NO$_3$-N), and LCK 350 (PO$_4$-P) (Co. Hach Lange, Düsseldorf, Germany).

2.4. Numerical Investigations—Set Up

The numerical model for the supporting simulations under variable conditions is conceptualized based on the column experiment with a similar spatial configuration (Figure 1). A one-dimensional (1D) model has been realized using HYDRUS 1D (V 4.17.0140, Co. PC-Progress, Prague, CZE, [21]), applying the Richards equation [30] for unsaturated flow with Mualem-van-Genuchten retention and relative hydraulic conductivity model [31,32].

The discretization of the space domain led to 146 mesh elements with a finer discretization at the topsoil. The TWWE and/or precipitation infiltration was implemented as a variable, time-dependent flux boundary condition (BC) on top of the column. The infiltration rates had been adopted from the experiments. The lower boundary condition was assumed to be a free drainage BC. Two materials with specific hydraulic properties were implemented in the model. The first one represented individual soil types in each column, and the other one used glass beads at the bottom of all the columns. Soil retention functions and hydraulic conductivities of these two materials were defined using the initial parameters extracted from laboratory tests (Table 1).

An inverse analysis based on observed water contents during joint infiltration of TWWE and precipitation events was performed by HYDRUS internally to optimize the initial parameters (Table 1) and to determine a final parameter set for each soil. Inverse methods are typically based upon the minimization of a suitable objective function, which expresses the discrepancy between the observed values and the predicted system responses. The system response was represented here by the numerical solution of the Richards equation, augmented with single porosity hydraulic model (Mualem-van-Genuchten) and mentioned boundary conditions. Initial estimates were then iteratively improved during the minimization process until the desired degree of precision was obtained. Here, water content observed by FDR probes with every 10 min interval during experimental runtime considered as an observed value. For the optimization of the objective function, a weighted least-squares approach based on the Levenberg–Marquardt nonlinear method is used in HYDRUS 1D [33].

The final parameter set is presented in Table 5; noticeable differences in residual and saturated water content can be identified as compared to the laboratory data. The pore connectivity parameter in the conductivity function was defined as $l = 0.5$ for all soils, following [31] respectively.

| Parameter                                         | Soil 1 | Soil 2 | Soil 3 | Soil 4 |
|---------------------------------------------------|--------|--------|--------|--------|
| Hydraulic Conductivity under full saturation K ($\text{cm day}^{-1}$) | 360    | 504    | 3939   | 2651   |
| Bulk density $\rho_b$ ($\text{g cm}^{-3}$)       | 1.68   | 1.70   | 1.67   | 1.65   |
| Van Genuchten shape parameter $\alpha$ ($\text{cm}^{-1}$) | 0.03   | 0.035  | 0.049  | 0.045  |
| Van Genuchten shape parameter $n$ (-)            | 2.58   | 1.96   | 2.75   | 2.05   |
| Residual water content $\theta_r$ ($\text{cm}^3 \text{ cm}^{-3}$) | 0.07   | 0.005  | 0.021  | 0.005  |
| Saturated water content $\theta_s$ ($\text{cm}^3 \text{ cm}^{-3}$) | 0.27   | 0.25   | 0.32   | 0.25   |
| Pore connectivity parameter in the conductivity function $l$ (-) | 0.5    | 0.5    | 0.5    | 0.5    |
The total simulation time for the scenarios with joint infiltration of TWWE and additional precipitation was 10,080 min (7 days). The precipitation events in the scenarios started for event 1 after 5230 min (Soil 1, 2 and 3)/5080 min (soil 4), for event 2 after 5040 min (soil 1, 2 and 3)/5140 min (soil 4) and for event 3 after 3900 min (soil 1, 2 and 3)/3700 min (soil 4). In general, they all started between morning and evening TWWE infiltration and lasted according to the event duration mentioned in Table 4.

3. Results and Discussion

3.1. Hydraulic Behavior

Water content observations (Figures 2 and 3, Supplementary Materials S2) indicate that the periods with higher values, caused by the daily infiltrations of only TWWE in the morning and evening hours, are followed by much longer periods of lower water content. These periods with higher and lower values are resulting from daily wet and dry phases, respectively. Moreover, the intermittent infiltrations (see Supplementary Materials S1) cause oscillations of water content in the upper observation points (Obs1). The retention of water in the dry phases is observed much lower in the soil with more permeability and smaller proportion of fine pores (Figure 3) than in the soils with lower permeability and higher fine pore content (Figure 2). Furthermore, the results indicate that periods with water contents close to full saturation are not existent, and thus, sufficient oxygen supply is expected during the infiltration of TWWE only.

Depending upon the hydraulic conductivity of the soils, it is already evident that the daily fluctuations of water content are influenced due to precipitation events. In case of the more intensive (event 2) and longer (event 3) events, steep increases in water content for both observation points are observed (Figure 2B,C and Figure 3B,C). However, these high soil moisture contents, less appropriate for high biological activity, decline rapidly after the end of the precipitation events. Therefore, it can be concluded that water contents are only temporally affected by the additional infiltration of water originating from precipitation events.

In the course of evaluating the obtained data, it should also be taken into account that 1D-column experiments may lead to an overestimation of water content compared to real-world conditions due to their dimensionality. The restricted lateral flow of the infiltrated water can lead to a higher degree of saturation [34,35]. Furthermore, preferential flow paths, such as the sidewall flow, can affect sensors positioned close to the sidewall [36,37].

A good agreement between observed and predicted water content for the upper observation point was achieved. However, for the lower observation point, the simulated water content showed a constant offset from observations but indicated a similar pattern of moisture fluctuations. One of the reasons could be the compaction of soils causing the apparent change of observed moisture distribution in the lower half of the column systems. Overall, the model outputs indicate that the time patterns of the fluctuating water contents during the joint infiltration of both TWWE and the additional water originating from precipitation events are in a moderate to good agreement. (Figures 2 and 3, Supplementary Materials S2).

Besides visual comparison, two error indicators were calculated to assess the quality of the conformity between observed and simulated water contents. Root Mean Square Error (RMSE), one of the commonly used error indicators, shows how well the simulated data represent the pattern of the observed data [38]. In principal applications, the lower the RMSE, the better the model performance [39]. In addition, percent bias (PBIAS), expressed as a percentage, assesses the averaged trend of the simulated data to be larger or smaller than the observed values [40]. The optimal value of PBIAS is zero, indicating accurate model simulation. In the case of positive values, the model is underestimating the water content while the model is overestimating the water content in case of negative values. PBIAS values up to ±25% can be considered as good to moderate fit [39].
The error indicators were calculated for the total simulation time of 168 h in the course of a precipitation event to see the overall trend of the fluctuating water contents including phases with normal TWWE infiltration as well as the joint infiltration of both TWWE and the additional water. Furthermore, RMSE and PBIAS were determined for the period mostly influenced by the precipitation events to see specifically how the system behaves during the additional infiltration of large amounts of water with strong changes in water contents within a short time (Table 6 and Supplementary Materials S3). While calculating RMSE and PBIAS values, a discretization of 10 min of observed and simulated data was applied throughout the considered simulation times.

![Graph A](image1.png)

![Graph B](image2.png)

![Graph C](image3.png)

**Figure 2.** Observed and simulated water contents before, during, and after precipitation event 1 (A), event 2 (B), and event 3 (C) for soil 1 for the upper (Obs1 and Sim1) and lower (Obs2 and Sim2) observation points.
Values for RMSE indicate an adequate fit between observed and predicted model data under consideration of other possible error sources. These include, for example, the heterogeneity of the soil, the used lower boundary condition in the numerical model (free drainage), which is not exactly representing the real conditions in the column, and the general accuracy of the FDR probes (± 2.5% as given by the manual [41]).

The negative and positive values of PBIAS indicate that the simulation is over- and underestimating the water content, respectively. This effect is more pronounced at the position of the lower sensor (Obs2). The possible cause could be the settlement of the soil over the experimental runtime and thus, more strongly changed soil characteristics in the lower part of the columns. Despite the over- and underestimation, the values for PBIAS are still in the range for good to moderate fitting.
Table 6. Model fitness of water content for the total simulation time of 168 h in the course of a precipitation event and for the period most influenced by the precipitation event for the upper (0.25 m below surface) and lower (1.15 m below surface) observation points for soil 1 and 4, RMSE (VWC) and PBIAS (%).

| Event | 0.25 m Below Surface | 1.15 m Below Surface |
|-------|----------------------|----------------------|
|       | 168 h Simulation Time | Precipitation Event | 168 h Simulation Time | Precipitation Event |
|       | RMSE     | PBIAS   | RMSE     | PBIAS   | RMSE     | PBIAS   | RMSE     | PBIAS   |
| Soil 1|          |         |          |         |          |         |          |         |
| 1     | 0.017    | −3.5    | 0.025    | −5.4    | 0.019    | −10.9   | 0.021    | −13.8   |
| 2     | 0.019    | −3.4    | 0.033    | −5.6    | 0.024    | −11.5   | 0.042    | −16.6   |
| 3     | 0.023    | −7.8    | 0.033    | −13.7   | 0.028    | −14.5   | 0.039    | −19.8   |
| Soil 4|          |         |          |         |          |         |          |         |
| 1     | 0.016    | −6.4    | 0.018    | −4.3    | 0.018    | 12.3    | 0.018    | 14.4    |
| 2     | 0.019    | 1.1     | 0.037    | −3.6    | 0.022    | 11.4    | 0.037    | 5.7     |
| 3     | 0.025    | 7.2     | 0.027    | 5.0     | 0.029    | 15.7    | 0.028    | 12.0    |

3.2. Water Quality and Purification Performance

At first, chemical analysis of the pore water samples for phases with only TWWE infiltrations indicate that the COD, the oxygen consumed for the oxidation of pollutants in the TWWE, is constantly reduced by at least 50% on the way through the unsaturated soil zone in all soils (Figure 4A,D,G and Supplementary Materials S4).

The reduction of infiltrated NH₄-N is observed by a minimum of 80%. (Figure 4B,E,H). Due to the reduction of ammonium in the course of nitrification processes, an increase in nitrate concentrations in the effluent is also observed. Denitrification processes hardly occur since the water contents were predominantly not in the range of full saturation, and thus, sufficient oxygen is available in the soil pore space due to the subsequent delivery over the soil surface (Figure 4C,F,I). At real sites, however, it is to be expected that the existing nitrate will be consumed for the oxidation of the remaining COD concentration in deeper soil layers due to the insufficient availability of oxygen. At least 50% of infiltrated nutrient PO₄-P is constantly reduced on the way through the unsaturated soil zone. However, the transport of remaining PO₄-P to streams and lakes by groundwater, which can cause eutrophication of these waters, cannot be excluded.

The purification performance, independent from the soil type, is almost unaffected by the additional infiltration of water originating from precipitation events (Figure 4 and Supplementary Materials S4). Analysis results of pore water indicate that the reduction of COD and PO₄-P is at least 50% and the degradation of NH₄-N reaches minimum 80%, similar to the phase with only TWWE infiltration. In the case of nitrate, a stronger dilution effect can be observed, resulting in a reduction of nitrate concentrations in comparison with only TWWE infiltration. However, it should be noted that the load of nitrate reaching the groundwater is not reduced at the same time. Nevertheless, with regard to the objective of the investigations, it can be stated that the joint infiltration of wastewater and rainwater does not lead to a reduction of the purification efficiency in the unsaturated soil zone.
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Event 1
Event 2
Event 3

Figure 4. Vertical chemical oxygen demand (COD)-concentration profiles, vertical NH₄-N concentration profiles, and vertical NO₃-N concentration profiles for soil 2 before and 24 h and 72 h after the precipitation event 1 (A–C), event 2 (D–F), and event 3 (G–I).

4. Conclusions

A significant increase in water content is observed by the infiltration of water originating from heavy precipitation events below on-site TWWE infiltration systems at sites with installed decentralized SWWTP. This effect raises uncertainties on the purification efficiency of TWWE constituents while percolating through the unsaturated soil zone.

Performed laboratory column experiments show that water contents of soils are only briefly affected by the additional infiltrated water. The elevated water contents below TWWE infiltration systems drop quickly to their initial values at the end of the precipitation events. Moreover, a fully saturated condition, which negatively influences biological activity, is never observed even when the extreme events are applied. Realistic numerical reproduction of the flow behaviors of percolated TWWE in the laboratory experiments supports the plausibility of these observations.
Observations also indicate a constant reduction of COD and phosphor as well as ammonium concentrations by a minimum of 50% and 80%, respectively, in the case of a single TWWE infiltration as well as for joint infiltration of TWWE and additional water originating from heavy precipitation events. No negative influence in the purification efficiency of TWWE constituents within the unsaturated soil zone was observed.

Ammonium degradation correlates with an increase in nitrate concentrations due to nitrification processes. Denitrification processes do not occur due to sufficient oxygen available in the soil pore space. Joint infiltration causes the dilution of the substance concentrations, especially for nitrate, but the load and thus mass transfer into lower layers or groundwater bodies in general is not affected.

Ultimately, this study reveals that, at least for the considered conditions, a negative effect on the purification efficiency regarding TWWE constituents in case of joint infiltration of both TWWE and additional water originating from precipitation events was not observed. Based on these observations, the overall risk for deterioration of the chemical status of the groundwater is assessed to be very low. Especially for shallow and therefore more vulnerable aquifers, the constant degradation of wastewater constituents for both single TWWE infiltration and joint infiltration shows that there is only a small risk arising for contamination of groundwater.

However, the results of the presented works only provide insights about the effects of joint infiltration of TWWE and additional water originating from precipitation events on the purification efficiency of TWWE constituents and should not be generalized. Therefore, future works should verify the presented findings by means of field investigations as real-world conditions including more complex subsurface features.

With regard to future laboratory investigations, the determination of a wider number of parameters (e.g., NO$_2$-N, Total N) should be performed. Thus, a better description of chemical processes taking place by the calculation of substance-specific mass balances is possible. In case of the availability of a sufficient database, software solutions such as PhreeqC can be recommended for that purpose.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2076-3417/10/9/3155/s1, Electronic Supplementary Materials S1: Table and figure of “Procedure of intermittent application of TWWE on the top of the soil layer according to hydrograph of the daily water consumption”, Electronic Supplementary Materials S2: Figures of “Observed and simulated water contents during and after the precipitation events 1, 2, and 3 for the upper (0.25 m below surface) and lower (1.15 m below surface) observation points”, Electronic Supplementary Materials S3: Tables of “Model fit to water content observation for the upper (0.25 m below surface) and lower (1.15 m below surface) observation points”. Electronic Supplementary Materials S4: Figures of “Vertical COD-, NH$_4$-N and NO$_3$-N concentration profiles before and 24/48/72 h after the precipitation events”

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