Authors' response

Dear Prof. Marnik Vanclooster, Associate Editor,

We thank you and the three anonymous reviewers for your time and effort. We believe that all of the comments were constructive, and we agree with most. Below you will find our detailed answer to each of the comments, including our action in the cases with which we agreed, and our explanation in the few cases that we do not. This is identical to the answers that we have posted on HESSD.
Please note that there is one comment that we initially chose not to accept (Reviewer #1) , but after receiving the same comment from Reviewer #2 we decided to accept that comment (MC3 in the comments of Reviewer #1 and SC6 in the comments of Reviewer #2). In addition to comments made by the reviewers we have identified several typos and corrected those as well. Following our point by point reply to each of the reviewers, you will find marked-up versions of the manuscript and supplementary material, denoting the changes, corrections and additions we have made. Added text or tables are marked in blue, deleted tables in red and deleted text is crossed with a line.

We believe that the revised manuscript is in much better shape and it is now ready for publication in HESS. On behalf of the authors, I would like to thank you and the three reviewers again for your help.

Sincerely,

Shany Ben Moshe

Response to Anonymous Referee 1

We would like to thank Anonymous Referee 1 for the comments. We will account for them in a revised version of the paper, as we report in the following point–by–point reply:

Major comments (MC)

MC 1 - *Emphasize the important result: long DP → deep aerated reactive interval, throughout the results and discussion (is it first result of its kind?).*

Autors' response - To the best of our knowledge, the presented results are the first to specifically show deep aeration following long DP in a SAT system. We, therefor, added this statement in the 'summary and conclusions' section. In addition, these findings are emphasized in the abstract, discussion and conclusions (L15, L190 and L289 respectively).

MC 2 - *The absence of reference to the flow in the column is annoying (e.g. flow rates, hydraulic properties of sediments; a simple 1D water flow model; more sophisticated flow of water and air model...). It is a controlled experiment in a column filed with porous medium, the hydrologist reader deserves a better acquaintance with this simple flowing system. The times of flooding and drying periods are meaningless without knowing the range of flow rates in the column. A calibrated model and simulations of different DP are a natural continuation of the research starting with the experiment, and can be in a following paper, but no reference of the flow condition in the column is not acceptable. Ponding and drying in a thick unsaturated-zone infiltration system is needed not only for the biochemistry, but also to sustain infiltration rates (see Ganot, Y.,R. Holtzman, N. Weisbrod, I. Nitzan, Y. Katz, and D. Kurtzman. 2017. Monitoring and modeling infiltration-recharge dynamics of managed aquifer recharge with desalinated seawater, Hydrol. Earth Syst. Sci., 21, 4479-4493).*

Autors' response - We fully accept the comment regarding the fluxes and added the appropriate values accordingly. Additionally, the manuscript of Ganot et al. (2017) is indeed important, and we have added reference to it in the introduction.
A numerical model,including water flow, solute transport, air movement as well as the main biogeochemical processes involved in the system was developed and calibrated. The results will be discussed in a separate manuscript that will hopefully be completed soon.

MC 3 - *Concentration units and naming chemicals entities – be consistent in naming and with units. Micro-molar than mg/l and in the N species is it as N or for the molecule?.I suggest use mg/l as C for DOC and mg/l as N for all N species thought the manuscript and say it explicitly. NO2- is an anion, "ammonium and NO3-", spell the chemical formula for the ammonium as well.*

Autors' response - According to the suggested, we made sure the chemical formula of ammonium is used throughout the text, with a few necessary exceptions in the M&M (i.e. "Ammonium test kit", "Ammonium chloride"). Concentration units of the results are consistently presented in mg/L, however, in the introduction we included some SHAFDAN concentration data in μM (the units used in the cited work). Since these numbers include analysis results and not only specific species (for example - DOC), we'd rather avoid the assumptions that are needed for the unit conversion.

MC 4 - *Figure captions are laconic. A figure and its caption should be much more standalone entities. For example: Figure 4 has no meaning for a reader without looking for "Experiment 3" in the text, while a few words can make it meaningful. Go over all captions.*

Autors' response -
The captions of all figures and tables were revised. The captions of Figures 2, 3, 4 and 5 were improved.

MC 5 -*Supplement - Sediment characteristics should be in the main text as part of dealing with comment # 2. A table of the chemical characteristics of all the water types should also be in the main text.*

Autors' response -
According to Referee 1's suggestion, water analysis results for the synthetic as well as the real TWW were moved from the supplementary material to the main text (Table 2 in the revised text). After careful consideration, we still believe that soil's characterization data belongs in the supplementary material for simplicity .

MC 6 - *Scientific-writing editing is needed. In many places a reference is referred to in both the beginning and the end of a sentence, synonyms with no explanation in abstract, typos, consistency (part 1 vs. – stage 1) if possible give meaningful names to the experiments – e.g. DP-240-SW or similar is better than meaningless experimant2/stage 2.*

Autors' response -
Scientific writing revision was performed for the manuscript. All the specific comments (SC) regarding writing editing were addressed. Experiments' names were changed to describe the DP and WW used (e.g. experiment 4 that involved DP of 240 min and real WW will be noted as - RW240)

Specific comments (SC)

SC 1 - *Abstract. Some numbers describing the main results in the abstract will help. For example in the deep layers DO stabilized on 1- 2 mg/l in the short DP and 3-4 mg/l for the long DP. Also % of removal of DOC TKN for the different DP.*

Autors' response -The abstract was re-edited. The revised version includes numerical values of the comparison between the DPs in terms of DO as well as water quality parameters.

SC 2 - *L13 – major comment (MC) 6*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 3 - *L18 "pseudo" why pseudo? It's a real reactor.*

Autors' response - A classic reactor typically is seen as a well-controlled, fully engineered and completely mixed system. We use the term 'pseudo-reactor' here to distinguish SAT from such reactor.

SC 4 - *L24 MC 6 typo*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 5 - *L38 I would say: local stream and the Mediterranean sea*

Autors' response - We accepted referee's suggestion.

SC 6 - *L41-42 MC 6*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 7 - *L51-52 MC 6*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 8 - *L52 – explain TKN = organic + ammonium nitrogen*

Autors' response - An explanation for the term TKN was added.

SC 9 - *L53 MC 3*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 10 - *L81 delete "roughly"*

Autors' response - Corrected according to the comment.

SC 11 - *"Untraditionally" not clear*

Autors' response - The reasoning behind the use of glucose as the carbon source in the synthetic wastewater is explained in L96-98. However, we accept that the use of the word 'Untraditionally' is not necessary and hence it was omitted.

SC 12 - *L100 rael→real*

Autors' response - Corrected according to the comment.

SC 13 - *L104 Table 1 - MC 5, MC 6*

Autors' response - Was addressed in MC 5 and MC 6.

SC 14 - *L105 "H4H8N2O3" should be I believe C4H8N2O3*

Autors' response - Corrected according to the comment.

SC 15 - *L114-115 MC 3, MC 5*

Autors' response - Was addressed in MC 3 and MC 5.

SC 16 - *L123 TKN defined before*

Autors' response - Corrected according to the comment.

SC 17 - *Figure 2 caption: 1) what panel for what depth (a, b,c..)? 2) The initial (residual) WC (∼ 15%) looks high for the sandy sediments in the column, explain.*

Autors' response - 1) Caption was improved and the letters (a-e) were associated with the corresponding parameters. 2) Albeit the fact that the soil profile is mostly sandy, it has non-negligible silt and clay content (see Table S5). Additionally, since the DP are not long enough for complete drying of the soil profile, the measured data doesn't reflect the residual WC even in the end of the DPs.

SC 18 - *L173 numbers do not fit the figure (12-18%) and not logical, larger DP → smaller WC makes more sense.*

Autors' response - We thank referee 1 for the attention. We corrected the numerical values.

SC 19 - *Figure 3 - MC 4 (big time). After making the figure +caption a standalone entity I would consider adding. At the caption: "note the convergence of the deep sensors to < 2 mg/l after the short DP versus convergence too > 3 mg/l in response to the long DP." or similar – MC1*

Autors' response - Was addressed in MC 4. We thank Referee 1 for the caption addition suggestion.

SC 20 - *L203 "(∼0.04..." are these the outflow concentrations? The inflow are orders of magnitude higher. Clarify.*

Autors' response - These are indeed outflow concentrations, it is mentioned in the text (L202). To make it clearer, the sentence was improved: "Outflow NH_4^+, DOC and TKN concentrations during experiment RW240 (∼ 0.04, ∼ 1.65 and ∼ 0.62 mg/L respectively) were significantly lower compared to their inflow concentrations"

SC 21 - *L204 missing a concentration (for NH4 I believe)*

Autors' response - We thank referee 1 for the attention. Corrected according to the comment.

SC 22 - *L 220-221 MC 6.*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 23 - *L 240-241 MC 6*

Autors' response - Corrected according to the comment (Addressed in MC 6).

SC 24 - *L252 Long FP means infiltration rates will decrease due to wetting front reaching some less permeable layers at depth. Draining the top sandy layers is essential also for maintaining high infiltration rates not only for the biochemistry.*

Autors' response - Addressed in MC 2.

SC 25 - *Figure 5 – in what depth is the ORP probe at Shafdan? MC 4*

Autors' response - The depth of the field ORP measurements is mentioned in L223. However, we added it to the caption of figure 5.

SC 26 - *L278 delete "quality"*

Autors' response - Corrected according to the comment.

SC 27 - *L296 Why "pseudo"? same as comment #3*

Autors' response - Addressed in SC 3.

Response to Anonymous Referee 2

We would like to thank Anonymous Referee 2 for his/her constructive comments. Most of the suggestions and comments were accepted and implemented in the revised version of the paper, as we report in the following point–by–point reply.

However, before we start we would like to put this research in the right perspective, from our point of view. SAT research combines earth sciences (hydrology, soil physics) with biochemical processes associated with wastewater treatment (i.e. processes like nitrification, de-nitrification, mineralization, etc). The terminology used in each of the disciplines may sound lacking to people from the other. Our perspective is closer to earth/geo sciences, looking at SAT processes without comparison to classic wastewater treatment, rather as processes that may be controlled and manipulated by the system's operational dynamics. We believe that some of the comments provided by the reviewer are due to this difference in perspective. But perhaps more importantly, our perspective in this study is to test the ability to conceptually change (and improve) SAT operation. While we do qualitatively compare our results to the SHAFDAN facility in Israel, the specific details of the site are less important than the concept that SAT sites (both in field and laboratory scale) should not be seen as a passive component of the wastewater treatment process but as a 'pseudo reactor' that may (and should) be controlled by hydraulic operation manipulations.

General comments (GC)

GC 1 - *... The basic notions of soil hydrodynamics are overlooked. Experimental variables such as hydraulic loading rate and saturated hydraulic conductivity of the soil are not mentioned which makes any comparisons with other studies complicated and makes it hard for the reader to understand initial and boundary conditions*
Autors' response: We fully agree - hydraulics were so trivial (to us) that we forgot to include it. Average flux (that is of the same order of hydraulic conductivity in our gravity driven system) is now included in the 'Materials and Methods' section.

GC 2 - *...In addition, the use of vague terms and notions such as flow rates, timing water content (WC) peaks or time to replenish oxygen concentration (instead of expressing mean water velocity or reoxygenation rate) is not acceptable.*
Autors' response: We agree in part with this comment. Where possible, terms were clarified. However, we do not see some of the terms suggested by the reviewer, adopted from the classic environmental engineering terminology, as being proper to SAT. Therefore we choose to keep some terms and avoid using terms that may be misleading (such as 'reoxygenation rate'), as we later elaborate in our response to the Technical comments (specifically -the technical comment referring to line 177).

GC 3 - *As an expert in water treatment technologies, one will find himself exasperated by the absence of a proper description of the biogeochemical parameters (e.g. characteristics of the wastewater such as chemical and biochemical oxygen demand, total suspended solids per liter of water, number of colony forming units per liter of water....) and by the improper use of units (see specific comments section). Such information should be mentioned and properly summarised*

in the main body of the article (not in the supplementary material) ...
Autors' response: We accept that wastewater chemical analysis data should be in the main text rather than the supplementary material. Therefore, we included this information for both the synthetic and real wastewater as Table 2 in the revised manuscript. However, we see this work as a conceptual attempt to discuss SAT operation and its effect on the biogeochemical state of the soil profile. Hence, the very specifics of the wastewater and soil, while important for the sake of completeness, are not the focus of this manuscript and could add unnecessary complexity to this type of paper.

GC 4 - *The experimental design of this study is quite impressive and definitely attracted my attention. However, it is disappointing that the take-home message of the study is quite trivial (i.e. longer drying periods allow for higher ORP values but mean less volume of water infiltrated per unit of time).*
Autors' response: This comment helped us understand that the main conclusions of this study were not highlighted well enough. It is true that qualitatively increasing DP will result in better oxygenation of the subsurface. However, the classic way SAT is being looked at is of a system where most of the oxidizing conditions (and hence removal of most of the ammonium and organic matter) happen in the very shallow subsurface. What we show here, we believe for the first time, is that longer DP also means extending the volume of the aerated subsurface, or increasing the volume of the 'pseudo-reactor', in our terminology. In other words, we extend the aerobically-active part of the system. We highlighted this conclusion in the revised 'Summary and Conclusions' section. We expect to further support our conclusions in a follow-up paper that includes the development and calibration of a full numerical flow and reactive transport model.

GC 5 - *The other conclusions are somehow weak and not put in a straigthforward manner. In addition, the train of thoughts of the authors is most of the time unstructured which makes this manuscript hard to read. The efforts made to carry out this study definitely should result in a greater contribution to the topic of management and operation of SAT...*
Autors' response: We thank the reviewer for this comment. The entire manuscript was revised and we believe it reads much better now. Moreover, in addition to the main points described above that are shown here for the first time in the context of SAT, the work described here assisted to develop a numerical model that will help to improve SAT operation under various conditions. Therefore, there will be a significant overall contribution both scientifically and practically (to SAT operation).

Specific comments (SC)

SC 1 - *(line 95) - What is the link between choosing glucose as the main source of carbon and the fact that enables the study of the behaviour of the system in field SAT ? Why is it not traditional ? Information is missing or this sentence should be restructured*
Autors' response: We accept that the word 'Untraditionally' is not clear and even confusing. Hence, we omitted it. Our original intention was to refer to the fact that glucose is usually not the only carbon source in treated wastewater. Nevertheless, since glucose is easily degradable by bacteria (compared to more complex carbohydrates or humic acids that might be present in wastewater) and is common in wastewater treatment and SAT research, its use as the main carbon source allowed us to sustain the short wetting and drying cycles implemented in our experiments and also work in the desired ORP ranges. We included this explanation in the

revised manuscript.

SC 2 - *(line 102) - What was the frequency of data acquisition by the sensors ? As a subsequent question, was there any data manipulation/processing (e.g. outlier removal, filtering and/or curve smoothing techniques) of the time series presented in the paper ? If yes, they should be described or at least mentioned. I am really impressed by the quality of the data. At first glance, the time series looked like modelling results to me.*
Autors' response: Data acquisition was every 1 minute. This information was added to the 'Materials ans Methods' section of the revised manuscript. The raw data was not manipulated or smoothened. The only processing step that was performed is correction of negative values recorded by the surface head sensor - when soil surface was completely dry the sensor would occasionally read small negative values. These values were set to 0. This is now clarified in the 'Materials and Methods' section of the revised manuscript.

SC 3 - *(line 115 to 119) - The authors mention the presence of pressure head sensors and soil solution sampling devices. Yet, no data regarding those sensors are shown. Why ? If the authors do not intend to show results, there is no need to mention their presence in my opinion unless it impacted the obtained results (e.g. disturbance of the flow regime at specific location, air intrusion,...).*
Autors' response: We fully accept the comment. The tensiometers and suction cups that were mentioned in the text were indeed used for qualitative verification of the flow and transport processes. However, since their results are not presented in this manuscript, we specifically stated it in the revised manuscript: "Tensio 150 (UGT GmbH) tensiometers for pressure head and ECO Tech Bonn (1.5 cm diameter) ceramics were installed along the column as well. While their data is not shown here, it fully supports our presented findings".

SC 4 - *(table 2) - Many space wasted and not many information contained in this table. If a proper (and scaled) schematic of the column was presented in figure 1, this table could be discarded.*
Autors' response: We accept the comment. In light of the changes we made in SC 3, this table seems to be of minor value to the reader. It was omitted from the revised manuscript.

SC 5 - *(line 126) - Comments valid for the whole "Results and discussion part". Since ORP values and oxygen transfer are investigated, it would make sense in my opinion to express WC in terms of relative saturation of water (WC divided by WC at saturation). By doing that, the reader can directly have an idea of which fraction of the pore space is either air-filled or water-filled. Same can be said regarding oxygen concentration which could be expressed as DO/DOsat if the temperature is known at any time of measurement.*
Autors' response: This indeed is a point that we had hard time deciding on. On one hand, as the reviewer states, normalized values may be more beneficial as they provide immediate and direct notation of aeration. On the other hand, most readers, so we feel, are more comfortable with actual water content values . Therefore we choose to leave values as are.

SC 6 - *(line 203) - The following holds true for the entire manuscript. The authors should pay extra attention to the use of units, specifically the ones for nitrogen species. What is expressed here ? milligrams of ammonium per liter of water OR milligrams of nitrogen in the form of*

ammonium per liter of water ? I suspect the latter but this should be clearly stated (especially in figure 4 where having a common y-axis for all sub figures is simply wrong!). If it is the latter, the notation should be NH4-N (mgN/l) for ammonium and NO3-N (mgN/l) for nitrate.
Autors' response: DOC and TKN analyses results are reported in our work in mg/L (of C and N respectively). For NO_3^- - and NH_4^+ we initially chose to use mg/L units (mg of the species per liter). However, we accept that consistent use of units is preferable and hence we now use $NO_3^- - N$ and $NH_4^+ - N$ in mg/L as was suggested .

SC 7 - *(line 220) (3.1 Comparison with field observations). The Israeli SHAFDAN SAT site is very poorly (if at all) described in the method section which makes comparisons difficult to interpret. Where is it exactly ? What is the mean annual temperature there? Under which conditions is it operated ? How is it comparable to the lab experiment conducted in Saxony ? If the point is to make a reliable comparison between the lab and field experiments, extra information should be added and this should be stated clearly as one of the purpose of the study in the introduction part.*
Autors' response: The SHAFDAN sites infiltration ponds' operation regime, location and and characteristics were described in multiple publications before. We, therefore, referred to some of them in the introduction and in the 'comparison with field observations' section (e.g. -Icekson et al., 2011, Goren et al.,2014). Section 3.1 of the manuscript shows qualitative agreement between the field and the columns experiments' results. Since the field and laboratory SAT systems are very different in many ways, and especially scale and dimensionality, this agreement is exceptionally interesting and points to the fact that regardless of the major scale differences, some of our findings (i.e. deep aeration and extension of the aerobically-active zone) are relevant to full scale field SAT systems. In that sense, the SHAFDAN site was merely the inspiration to this chapter and not the focus of it. Nevertheless, to allow the reader easy access to the full information, we included a short description of the SHAFDAN site in the beginning of section 3.1. In addition, a comprehensive description was added to the revised 'supplementary material' document.

Technical comments

Referee 2's technical comments are summarized in the following PDF file:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2019-371/hess-2019-371-RC2-supplement.pdf
Autors' response: A full revision of the manuscript was performed. Minor comments (e.g. typos, word selection suggestions etc.) were corrected according to referee's suggestions. More general comments are addressed below:

Figures - Referee suggested multiple adjustments to the figures.
Autors' response: We carefully considered each of the specific comments and we believe that all figures were improved thanks to Referee 2's constructive comments. Specific changes we made according to the comments are hereby reported:
Figure 1: The labels denoting the modules of the column were omitted and the port positions labels were adjusted to a bigger font.
Figure 2: According to Referee 2's suggestion, we added the depths next to each of the a-e sub-plots.
Figure 3: We accepted Referee 2's suggestion to separate the different stages of the experiment by a dashed line and added a clear label denoting 'stage 1' and 'stage 2'. We accept that a presentation of the x-axis in 'days' might be easier to read for long time-series. However, for a system that operates at cycles of hours with no meaning to day/night (sunlight), we feel that

this will not help, rather it will make the presentation cumbersome. For example, our FP will be 1/24 days). Therefore, we would rather keep time units in minutes.
Figure 4: The legend of the figure was corrected according to the comment. However, we disagree with the idea of connecting measurements with a straight line. A line connecting two data points implies that a linear trend is assumed. We do not assume that and thus, we believe that singular data pints are more suitable for this figure.
Figure 5: According to Referee 2's suggestion, we changes the y-axes of both sub-plots (Figure 5 a and b) to have the same range of values. The depth of the field measurements was added to the caption of the figure (note that it is also mentioned in Line 223). However, we disagree with the notion of connecting ORP measurements with a straight line. In addition to the above, in the case of the field data, each point represent an independent infiltration campaign. Hence, connecting the dots would not describe accurately the presented data.

Line 26 - DOC, NH_4^+ and organic nitrogen concentrations of secondary effluent at the SHAF-DAN site are presented in μM. Referee suggested to convert to mg/L
Autors' response: We accept Referee's suggestion. Units were converted to mg/L.

Line 86 - Referee commented that the terms Flooding periods (FP) and Drying periods (DP) were defined before.
Autors' response: The terms FP and DP were indeed defined before. However, this sentence was specifically phrased to clarify authors' interpretation of the terms as it was used throughout the manuscript. Thus, in this case we believe the current wording is appropriate.

Line 135 - Authors included timing of the water front. Referee commented that this information is not informative
Autors' response: We accept the comment. This line was omitted.

Line 136 - Authors mentioned 'classic infiltration theory'. Referee suggested to refer to a specific model
Autors' response: We accept the comment. By 'classic infiltration theory' we intended to refer to simple sharp-front models such as the Green and Ampt infiltration model. We added this information in the revised manuscript.

Line 147 stated "As observed in multiple studies in laboratory and field work, close to the surface, DO concentrations are expected to increase in response to the soil aeration during the DP since regardless of the oxygen movement mechanism (diffusion, advection or convection), the short distance ensures fast response of the system". Referee commented that this is not new information
Autors' response: This is indeed known information that was previously shown by others. We included this line to emphasize the difference between the expected oxygen recovery behaviour in the shallow parts of the profile compares to the deeper parts (that are discussed in the next paragraph)

Line 162-163 - Referee commented that the sentence is missing the subject and thus is not meaningful

Autors' response: We thank Referee 2 for the attention. The sentence was corrected.

Line 177 - Referee suggested to calculate re-oxygenation rate instead of the use of the term 'oxygen recovery'.
Autors' response: We thank Referee 2 for the suggestion. We acknowledge that re-oxygenation rates may be valuable information for the understanding of some reactors or filters that are well-mixed or of fixed volume. In this case, however, the increase in DP in response to the longer DP varied between the different depth of the column. For example - while the deepest parts of the column were able to sustain DO concentrations of ~3 mg/L (during the longer DP experiments), the term 're-oxygenation' does not accurately describe the system's behavior. Further, one of our main findings is the relation between DP and the 'oxidizing volume'. After careful consideration, we believe that the use of the term 'DO recovery' is more suitable for the purpose of the sentence.

Line 186 - Authors stated: "Considering the fact that sustaining the shorter DP of stage 1 (of experiment 2) would result in total DO depletion ~175 cm depth (supplementary material), these are very important observations. Referee commented that the importance of the sentence is not clear to him/her.
Autors' response: This line expresses one of the important points of our work. Studies have shown before that long DP are beneficial for the upper ~ 1 meters of a SAT profile in terms of DO concentrations and oxidation rates. While this is correct, we demonstrated here that deeper areas (in this specific sentence ~175 cm depth) displayed a significant DO increase in response to the longer DPs. This means that longer DPs lead to extension of the aerobic volume of the SAT 'pseudo reactor'. The referral to the fact that sustaining the shorter DPs would lead to complete oxygen depletion in this depth is important for comparison reasons, but we believe that displaying the figure in the main text does not add additional value to the purpose of the claim.

Line 205 - Authors reported α value for the statistical t-test performed. Referee suggested to display p_value instead.
Autors' response: In the text, we use phrases such as 'significantly higher concentrations' to denote the statistically significant difference in outflow concentrations between experiments 3 and 4. To provide the reader with the information on the significance level we chose for the tests, we report the α value that was the same for all the concentration pairs examined in the t-tests (i.e. DOC, TKN and NH_4^+).

Line 254 - Authors stated that inflow DOC, TKN and NH_4^+ content was matched between the synthetic and the real wastewater. Referee pointed this information should be stated in the 'methods' section.
Autors' response: Although the review provided was very detailed, this was probably missed. This information is stated in the 'Materials and Methods' section (Line 113).

Lines 262-272 - Referee pointed that this paragraph is too vague and hard to follow.
Autors' response: This section was completely revised. The revised paragraph includes a comparison of our findings to a paper by Ak et al.,2013, that compared organic matter removal in a series of column experiments with synthetic and real WW. We discuss the similarities be-

tween their results and our findings and also the differences and the possible reasons for them. We believe the revised paragraph is much clearer and better reflects the concept it addresses.

Summary and conclusions - Referee pointed that there is a change in tense between the first and second paragraphs.
Autors' response: We thank referee 2 for the attention. The 'Summary and Conclusions' section was fully revised and all comments were addressed

Response to Anonymous Referee 3

We would like to thank anonymous Referee 3 for his/her constructive comments. We will account for them in a revised version of the paper, as we report in the following point–by–point reply:

General comments (GC)

GC 1 - *One of the most important phenomenon, from my point of view, is the issue of SS that is not addressed at all in this article while it is the main problem when applying treated wastewater on a soil (clogging).*
Autors' response - We agree that this is indeed an important topic and its investigation is crucial for SAT sustainability. As reflected by the consistency in surface head and WC patterns along the flooding and drying cycles - we did not observe significant clogging in our system and hence we did not discuss it in the paper. However, since we very much agree that in field scale (or real) systems clogging is a major issue - we now shortly discuss it in the 'Comparison with field observations' section.

GC 2 - *In general English and spelling (words are often singular when they should be plural) should be reviewed for a better reading of the article. Put dots for numbers and not comma.*
Autors' response - According to Referees' general and specific comments, the entire text was revised. Grammar and spelling mistakes spotted by the Referees or found by the authors in the revision process - were corrected.

GC 3 - *When we talk about dissolved oxygen, it is better to write its unity in mgO2/L instead of mg/L for better understanding.*
Autors' response - We agree that the presentation of concentrations should indicate the correct species measured by the measuring analytical tool used / sensing device. However, as oxygen is dissolved in water as O_2, it is very acceptable and common to present its concentrations as mg/L (given that the species is noted as DO). We agree that Referee's suggestion is also a valid form of presentation but in this case we choose to leave the notations as they are currently presented.

GC 4 - *Generally, when we talk about nitrogen, concentrations are expressed in mgN/L. Is this the case in this article? For example, Figure 4 shows values but the indicated parameters are NH4+ and NO3-. Is it NH4-N and NO3-N?*
Autors' response - We accept Referee's suggestion and we now use $NO_3^- - N$ and $NH_4^+ - N$ in mg/L .

Specific comments (SC)

Introduction

SC 1 - *Lines 26-27: the units used for DOC, ammonium and organic nitrogen are not expressed in the system of international units (mg/L)*
Autors' response - We accept Referee's comment. Units were converted to mg/L.

SC 2 - *Lines 40-42: repetition of Goren et al. (2014)*
Autors' response - Corrected according to comment.

SC 3 - *Lines 51-52: repetition of Mienis et al. (2018)*
Autors' response - Corrected according to comment.

Materials and Methods

SC 4 - *Line 78: the reference to Table 1 is not good. Table 1 does not refer to sensors and sampling equipment but to the characteristics of the applied water as well as to the duration of the flooding and drying phases.*
Autors' response - We thank Referee 3 for the attention. As part of the complete revision of the manuscript, this table was omitted. The sensors we used are now described in the last paragraph of the 'Materials and Methods' section.

SC 5 - *Table 1 and Table 2 must be reversed.*
Autors' response - As mentioned above, according to Referees' comments, Table 2 (that originally described sensors' position) was omitted. Following Table 1, we now present the TWW composition.

SC 6 - *Lines 95-97: the sentence should be rewritten to be clearer.*
Autors' response - We accept the comment and made improvements accordingly: "Glucose was chosen as the main carbon source for two reasons: in addition to the fact that it is often used in synthetic WW for laboratory SAT systems (Essandoh et al., 2011; Ak et al., 2013), its high consumption rate by bacteria (compared to more complex carbohydrates or humic material) allowed the investigation of the system's behavior around the ranges of ORP values that are found in field SAT systems (Orgad et al., 2017)."

SC 7 - *Line 100/Table 1: why call the inflow of experiments 3 and 4 "Real TWW" while additions of glucose and ammonium have been made? If the explanation comes later, put it here.*
Autors' response - The TWW for the third and fourth experiments were collected from the Dresden WWTP after an activated sludge process. This means that the microbial community present in the TWW itself was inherently different than the synthetic WW (that were prepared with tap water). The addition of glucose and NH_4^+ was necessary in order to equalize the inflow DOC, TKN and NH_4^+ concentrations between all four experiments. A more precise term would be "ammended real wastewater", but that would be cumbersome. We did clarify the terminology in the sentence, which reads now: " The real TWW used for experiments RW150 and RW240 were enriched with glucose and NH_4^+ after initial chemical analysis (presented in the supplementary material) to match the NH_4^+, TKN and DOC concentrations to these of the synthetic TWW."

SC 8 - *Table 1: in experiment 3, in the line "inflow" it misses the letter "T" because it is treated wastewater that was added and not raw wastewater.*
Autors' response - We thank Referee 3 for the attention. Corrected according to comment.

SC 9 - *Line 102: the sentence starting with "During all experiment, ..." should be the beginning of a new paragraph because it concerns ALL the expermientations and not only the experiment 3 and 4. Refer to Table 2. By the way, it lacks an S to "experiment".*
Autors' response - As part of this section's revision, we moved this line to the last paragraph of the 'Materials and Methods' section (that describes the sensors). It is now in a separate paragraph as was suggested. Typo was corrected according to comment.

SC 10 - *Lines 112-114: the first sentence has already been mentioned above (line 100) and the second sentence should be after line 100.*
Autors' response - This line was improved: "The real TWW used for experiments RW150 and RW240 were enriched with glucose and NH_4^+ after initial chemical analysis. (presented in the supplementary material) to match the NH_4^+, TKN and DOC concentrations to these of the synthetic TWW. Final $NH_4^+ - N$, TKN and DOC concentrations for the synthetic and real WW are resented in Table 2". However, we think the second part of the sentence, referring to the enrichment of the TWW belongs in this line (and not in line 100) since we believe this information should appear after the description of the synthetic WW composition.

SC 11 - *Lines 121: remove the ":" which would indicate a list behind whereas here the different compounds and their methods of determination are separated by dots.*
Autors' response - We fully accept the comment. The four methods used are now separated by ';'.

SC 12 - *Line 121: why do you write "ammonium" and not NH4+ whereas it has already been defined line 85? True for the whole document.*
Autors' response - We accept that consistent use of the chemical formula of ammonium (NH_4^+) is preferable. Hence, we now use it throughout the manuscript.

SC 13 - *Line 122: it misses the sign "-" behind NO2.*
Autors' response - We thank Referee 3 for the attention. Corrected according to comment.

Results and Discussion

SC 14 - *Lines 140-142: repetition of Haaken et al., 2016*
Autors' response - Corrected according to comment.

SC 15 - *Line 169: you say ∼50 minutes on average for part 1 whereas you said line 132 ∼ 80 minutes. Be consistent.*
Autors' response - We thank Referee 3 for the attention. This error was corrected.

SC 16 - *Line 179: 3 digits after the decimal point for the minutes are not necessary (2.7 minutes instead of 2.700 minutes).*
Autors' response - In this line, the commas (e.g in 2,700) do not symbolize a decimal points but thousands separators.

SC 17 - *Line 186: 'around' is not necessary because you write "∼ ". Moreover, write "for the 375 cm sensor" and "for the 575 cm sensor" instead of "in the 375 cm sensor" and "in the 575 cm sensor".*
Autors' response - The word 'around' was omitted as suggested. However, we do not believe the word 'for' is suitable for the purpose of this sentence.

SC 18 - *Lines 194-195: again, this information has already be written line 100.*
Autors' response - As this is the first time in the results and discussions section that data with real TWW is presented, we think it is important to remind the difference between these experiments and the former ones. However, we accept the comment and the sentence, that now reads " In these experiments we used real TWW" was shortened.

SC 19 - *Figure 4: it would be better to display the input concentrations on the graphs to better see the differences between input and output for experiments 3 and 4.*

Autors' response - As mentioned in the text, input parameters (DOC, TKN and NH_4^+) were the same for both experiments (inflow concentrations are presented in Table 2 in the main text). Since the aim of this figure is to show the difference between the two experiments, we believe that addition of the input concentrations will add unnecessary complexity to the figure.

SC 20 - *Lines 203 and 205: the numbers in the parentheses are the differences between the concentrations measured at the input and those measured at the output for the experiments 3 and 4? I think that it is not wise to express the efficient removal in terms of differences in concentrations but you should rather express these removal efficiencies in terms of percentage.*
Autors' response - The numbers in parentheses represent outflow concentrations. We accept that this is not clear from the sentence and hence we improved its structure: "Outflow $NH_4^+ - N$, TKN and DOC concentrations during RW240 ($\sim$ 0.033, $\sim$ 0.62 and $\sim$ 1.65 mg/L respectively) were significantly lower compared to their inflow concentrations . During RW150, $NH_4^+ - N$, TKN and DOC outflow concentrations ($\sim$ 0.5, $\sim$ 3.8 and $\sim$ 4.4 mg/L, respectively) were also lower compared to the inflow, but averaged significantly higher compared to RW240 (t-test, α=0.05) ..

SC 21 - *Line 203: you say that your measurements correspond to what is measured in the full scale SAT site but we have no table, figure, or at least a reference on which your statement is based.*
Autors' response - Figure 5 was designed specifically to demonstrate this claim. The data presented in Figure 5a is based on field observations from one of the SHAFDAN's infiltration ponds, as explained in detail in the 'Comparison with field observations' section.

SC 22 - *Line 253: Table 1 should be Table 2.*
Autors' response - As was mentioned before, the original Table 2 was omitted.

Summary and Conclusions

SC 23 - *Line 280: 150 minutes or 240 minutes (and not only 240 m which means meter).*
Autors' response - We thank Referee 3 for the attention. Corrected according to comment.

On the role of operational dynamics in biogeochemical efficiency of a soil aquifer treatment system

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Abstract. Sustainable irrigation with treated wastewater (TWW) is a promising solution for water scarcity in arid and semi-arid regions. Soil aquifer treatment (SAT) provides a solution for both the need for tertiary treatment and seasonal storage of wastewater. Stresses over land use and the need to control the obtained water quality makes the optimization of SAT of great importance. This study looks into the influence of SAT systems' operational dynamics (i.e. flooding and drying periods) as well as some aspects of the inflow biochemical composition on their biogeochemical state and the ultimate outflow quality. A series of four long-column experiments was conducted, aiming to examine the effect of different flooding/drying period ratios on dissolved oxygen (DO) concentrations, oxidation-reduction potential (ORP) and outflow composition. Flooding periods were kept constant at 60 minutes for all experiments while drying periods (DP) were 2.5 and 4 times the duration of the flooding periods. Our results show that the longer DP had a significant advantage over the shorter periods in terms of DO concentrations and ORP in the upper parts of the column as well as in the deeper parts, which indicates that larger volumes of the profile were able to maintain aerobic conditions. DO concentrations in the deeper parts of the column stabilized at ∼3-4 mg/L for the longer DP compared to ∼1-2 mg/L for the shorter DP. This advantage was also evident in outflow composition that showed significantly lower concentrations of $NH_4^+ - N$, DOC and TKN for the longer DP (~ 0.03, ~ 1.65 and ~ 0.62 mg/L respectively) compared to the shorter DP (~ 0.5, ~ 4.4 and ~ 3.8 mg/L, respectively). Comparing experimental ORP values in response to different DP to field measurements obtained in one of the SAT ponds of the SHAFDAN, Israel, we found that despite the major scale differences between the experimental 1D system and the field 3D conditions, ORP trends in response to changes in DP, qualitatively match. We conclude that longer DP not only ensure oxidizing conditions close to the surface, but also enlarge the active (oxidizing) region of the SAT. While those results still need to be verified in full scale, they suggest that SAT can be treated as a pseudo-reactor that to a great extent could be manipulated hydraulically to achieve the desired water quality while increasing the recharge volumes.

1 Introduction

Water shortage in arid and semi-arid regions leads to great difficulties sustaining local agriculture which have many economical as well as social and environmental implications (Garcia et al., 2014). The use of treated wastewater (TWW) for irrigation is widely accepted as one of the means to reduce agricultural water scarcity (Negewo et al., 2011). While biological treatments like activated sludge are highly efficient in terms of pollutant removal, the TWW they generate usually does not meet regulatory standards for unrestricted crop irrigation (Tanji et al., 1997) or poses a sustainability question mark on their practice (Assouline et al., 2016). For example, in the Israeli Dan region wastewater treatment plant (the SHAFDAN site), following the activated sludge secondary treatment, TWW have low to moderate organic load. Dissolved Organic Carbon (DOC) is $\sim$ 10.8 mg/L, $NH_4^+ - N$ is $\sim$ 4.2 mg/L and organic nitrogen is $\sim$ 1.25 mg/L (Icekson et al., 2011). However, for the TWW to meet regulatory standards for unlimited irrigation, further water quality enhancement is required (Shuval et al., 1986). Soil aquifer treatment (SAT) may be the supplementary treatment component for conventional (secondary) WW treatment, that is needed to meet regulations and sustainability. These systems involve clusters of infiltration ponds through which TWW is infiltrated through the vadose zone, into the aquifer in cycles of flooding and drying. This form of operation (i.e. flooding and drying cycles) is important for both sustaining infiltration rates (Ganot et al., 2017) and rates of microbially driven oxidation and reduction processes. . In the ponds and subsequently in the unsaturated zone, residual dissolved organic carbon (DOC) and other nutrients (like organic and inorganic nitrogen species) are involved in biogeochemical processes (such as adsorption to the soil minerals, consumption by bacteria etc.) which result in further decrease in the TWW's organic load and overall improved chemical composition (Bouwer et al., 1991; Amy et al., 2007).

In Israel, $\sim$ 150 million m^3 of wastewater (WW) are treated each year in the SHAFDAN facility (Icekson et al., 2011). After the SAT process, the TWW is transported to the south of Israel and is used by farmers for crop irrigation (Idelovitch et al., 2003). With the constant rise in population, the site is often not able to treat all the WW it receives, which results in conventionally treated WW being discarded to the local streams and the Mediterranean sea . Clearly, the SAT component is the bottleneck for full utilization of TWW. The SAT mechanism relies on the various biogeochemical processes that take place during TWW infiltration. These processes begin even before the TWW reach the unsaturated zone. Goren et al. (2014) described the variability in carbon and nitrogen species through the hours of the day and in different seasons in a field study conducted in the SHAFDAN site. They found that the chemical composition of the TWW in the infiltration ponds responded to the day and night cycles. For example, during daytime, dissolved oxygen (DO) concentrations increase due to photosynthesis, reaching a maximum in the late afternoon. As a result, TWW that are infiltrated during the day are significantly more oxidized compared to TWW that is infiltrated during the night, affecting the redox state of the soil profile and thus impact rates of oxidation reactions. Once the TWW reaches the unsaturated zone, oxygen concentrations become a limiting factor that affects the efficiency of some key biogeochemical processes that are crucial for the enhancement of the TWW quality. The role of oxygen as a limiting factor in SAT systems is especially prominent in the deeper areas of the vadose zone where natural aeration during the drying periods (DP) is limited. DOC and nitrogen species' degradation during infiltration depend heavily on processes like aerobic bacteria respiration and nitrification for which DO concentrations are of great importance (Goren et al., 2014). Mienis et al. (2018) studied nitrogen behavior under the SHAFDAN's infiltration ponds through 40 years of operation . In their study, concentrations of NH_4^+, Total Kjeldahl Nitrogen (TKN; The total concentration of organic nitrogen and NH_4^+) and oxidized nitrogen species (NO_2^-, NO_3^-, NO) were monitored , using data from two observation wells, screening different depths of the vadose zone. They found that removal of up to ∼ 75 % of the total nitrogen occurred in the upper parts of the soil profile (up to $\sim 70cm$ below ground surface) while the deeper parts had a smaller contribution. This observation led them to the conclusion that inflow concentrations of more than 8.3 mg/L of $NH_4^+ - N$ will result in a decrease in reclaimed water quality due to NH_4^+ and organic nitrogen leakage into the aquifer. Previous research regarding oxygen behavior in the vadose zone during wetting and drying cycles (Kim et al., 2004; Dutta et al., 2015) emphasize the role of the site's operational dynamics in the reclaimed water quality. During the flooding periods (FP), water content (WC) in the soil profile below the infiltration pond gradually increases (Arye et al., 2011), limiting the scope of diffusive and advective aeration which is crucial for the replacement of the DO used by bacteria. Hence, DP play a major role in the overall biogeochemical dynamics of SAT systems (Miller et al., 2006). Looking at oxygen dynamics during wetting and drying cycles in a 1-meter sand column, Dutta et al. (2015) found that DO concentrations dropped exponentially in response to each flooding event. They also showed that oxygen partial pressure recovered to its initial value upon the start of the DP. This observation, however, may not hold true for greater depths . In a field scale study, Miller et al. (2006) described oxygen and nitrogen species concentrations in a ∼ 2.7 m sandy loam soil profile during cycles of 4 days of wetting and 4 days of drying. They found that deeper than 0.6 meters below ground surface, aeration was limited compared to the upper parts of the profile and that deeper than 1.5 meters, the vadose zone was mostly anoxic throughout the wetting and drying cycles (Miller et al., 2006).

In this study we examine the effect of hydraulic operation (i.e. wetting-drying periods) on a 6-meter soil profile's biogeochemical dynamics through a series of long-column experiments. We hypothesize that in vadose zones deeper than ∼ 1-1.5 meters, oxidation-reduction potential (ORP) and DO dynamics differ greatly compared to the shallow parts of a soil profile and are affected to a different extent by changes in hydraulic management and inflow composition. We further hypothesize that insufficient DP will have a detrimental effect on the deeper parts of the soil profile and they will eventually result in DO depletion, negative ORP and impaired outflow quality. Correspondingly, increased DP will be especially significant for the deeper parts of the profile which may lead to extension of the aerobic zone to greater depths. Four main long-column experiments were designed to examine the effect of shorter and longer DP as well as inflow composition on the biogeochemical state and dynamics of the soil-water system at different depths and the ultimate outflow chemical composition (especially DOC and nitrogen species).

2 Materials and Methods

A 6-meter long, 15 cm diameter stainless steel column was designed. The column consists of six one-meter modules, each module is equipped with ports for sensors and sampling equipment. Sensors were located in ports 1, 3, 5, 7, 9 and 13 (Fig.1). Data acquisition frequency from all sensors was 1 minute. The column was packed with soil from the SHAFDAN site according to the soil horizons at the site. The different layers' texture as well as initial total organic carbon (TOC) content were determined and are described in the supplementary material (Fahl et al., 2014).

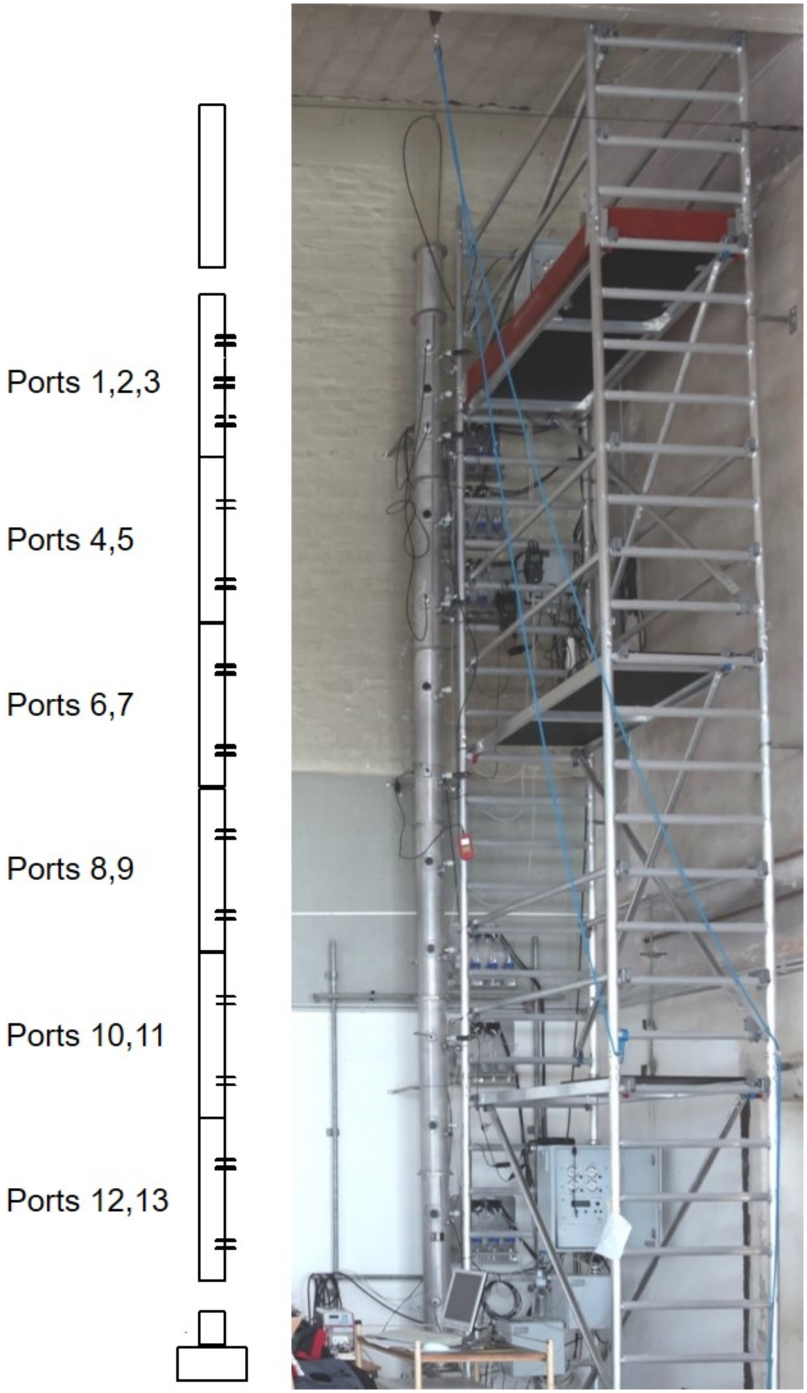

Figure 1. The six-meter long column, Dresden, Germany. Sensors were located in ports 1, 3, 5, 7, 9 and 13

Prior to the four main column experiments (Table 1), a preliminary flow experiment was conducted in order to estimate the average flow rate through the column as well as the ponding rate. Average flux during infiltration was estimated to be ~0.4 cm/min. The first experiment involved a simple inflow solution of only NH_4^+ (added to tap water, final concentration of $\sim$ 4.5 mg/L of $NH_4^+ - N$), where the hydraulic operation consisted of cycles of 60 minutes of flooding followed by 150 minutes of drying. The term 'flooding period' (FP) refers to the duration of time during which water is pumped to the top of the column. A 'drying period' (DP) starts as the pump is turned off and ends at the beginning of a new flooding event. These specific flooding and drying periods were chosen in light of the preliminary experiment's results , in which it was shown that a DP of 150 minutes is sufficient for the ponding water to infiltrate and allows around 60-70 minutes of free aeration (i.e. no ponding). One of the goals of the preliminary as well as the first experiment was to "awaken" the microbial community of the soil system. The second experiment involved the preparation of a synthetic TWW inflow solution which included NH_4^+, glucose and asparagine dissolved in tap water ~~(for exact solution composition - see supplementary material)~~. The synthetic TWW composition was designed to include a moderate-to-heavy load of DOC as well as organic and inorganic nitrogen species around the concentrations found in the SHAFDAN ponds. ~~Glucose was chosen as the main carbon source to allow the investigation of the system's behavior around the ranges of ORP values that are found in field SAT systems at various depths and under different hydraulic loads and operation regimes~~ Glucose was chosen as the main carbon source for two reasons: in addition to the fact that it is often used in synthetic WW for laboratory SAT systems (Essandoh et al., 2011; Ak et al., 2013), its high consumption rate by bacteria (compared to more complex carbohydrates or humic material) allowed the investigation of the system's behavior around the ranges of ORP values that are found in field SAT systems (Orgad et al., 2017).

Hydraulic operation for the second experiment included two stages (stages 1 and 2) - we first applied cycles of 60 minutes of flooding and 150 minutes of drying, and after 9 cycles the DP were increased to 240 minutes. During the third and fourth experiments, real TWW water from the Dresden-wastewater treatment plant (WWTP) were used. Hydraulic operation included 60 minutes flooding periods for both experiments and DP were 150 minutes in the third experiment and 240 minutes in the fourth. ~~During all experiment, sensors' information was recorded and pore solution samples were taken from depths of 25, 75 and 175 cm below soil surface as well as from the outflow. Inflow solution was also sampled and tested to confirm that no major changes in its composition occurred during the experiments.~~ Experiments 1,2 (stages 1 and 2), 3 and 4 are noted here as AS150, SW150, SW240, RW150 and RW240 respectively, where the abbreviations AS, SW and RW denote the TWW source (Ammonium solution, synthetic TWW and real TWW respectively) and 150/240 denotes the length of the drying periods in minutes.

Table 1. Inflow composition and flooding / drying periods in the four discussed experiments

Experiment	AS150	SW150/240	RW150	RW240
Inflow	NH_4^+ solution	Synthetic WW	Real TWW	Real TWW
FP / DP (min)	60/150	SW150 60/150 SW240 60/240	60/150	60/240

For the synthetic TWW solution the following chemicals were used : L-Asparagine anhydrous ($C_4H_8N_2O_3$, $> 99.5\%$, Sigma Aldrich), Ammonium chloride NH_4Cl (Jenapharm-Laborchemie APOLDA, Analysis pure), D(+)-Glucose monohydrate $C_6H_{12}O_6 \bullet H_2O$ (VWR chemicals PROLABO). Solutions were prepared by slowly adding the appropriate amount of powdered chemical into the needed amount of distilled water (DW) while continuously stirring the solution using a magnetic stirrer. Large amounts of synthetic TWW (~200 liter for experiments AS150 and SW150/240) were prepared by adding concentrated solutions of the desired chemicals into the remaining amount of tap water (200 liter minus the amount added as concentrated solutions) so that the final desired concentrations were reached. The synthetic TWW solution was then gently mixed. The real TWW used for experiments RW150 and RW240 were collected from the Dresden (WWTP) were enriched with glucose and NH_4^+ after initial chemical analysis (presented in the supplementary material) to match the NH_4^+, TKN and DOC concentrations to these of the synthetic TWW. Final $NH_4^+ - N$, TKN and DOC concentrations for the synthetic and real WW are resented in Table 2.

Table 2. Chemical composition of the synthetic WW and the real WW after fortification

Analysis	Synthetic TWW	Real TWW
$NH_4^+ - N$	3.8 mg/L	3.8 mg/L
TKN	9.2 mg/L	10.1 mg/L
DOC	103 mg/L	102 mg/L

During all experiments, sensors' information was recorded and pore solution samples were taken from depths of 25, 75 and 175 cm below soil surface as well as from the outflow. Inflow solution was also sampled and tested to confirm that no major changes in its composition occurred during the experiments. Sensors along the column included frequency domain reflectometers (FDR) sensors for soil moisture measurement were SM300 (Delta-T Devices Ltd), submersible Level Sensor (Sensortechnics) was used for Surface head. LDO10101 (Hach-Lange, Germany) were used for luminescence dissolved oxygen (LDO), and Harburg (ELANA Boden Wasser Monitoring) sensors were used to monitor ORP. Tensio 150 (UGT GmbH) tensiometers for pressure head and ECO Tech Bonn (1.5 cm diameter) ceramics were installed along the column as well. While their data is not shown here, it fully supports our presented findings . FDRs, WC and DO sensors were located at depths of 25, 75, 175, 275, 375 and 575 cm. ORP sensors were locates in the two upper ports (25 and 75 cm depth).

Table 3. Sensors' position along the column (DELETED)

Soil surface	SH sensor	-	-	-
25 cm	FDR	LDO	Suction cup	ORP
75 cm	FDR	LDO	Suction cup	ORP
175 cm	FDR	LDO	Suction cup	
275 cm	FDR	LDO	-	-
375 cm	FDR	LDO	-	-
575 cm	FDR	LDO	-	-

To assess the chemical composition of the inflow solution as well as the collected samples, four types of chemical analysis were performed: NH_4^+ was measured using ammonium test kit and a Nova 30 Spectroquant (Indophenol blue method) ; NO_2^- and NO_3^- concentrations were measured using an Ion chromatograph (IC) after samples were passed through a 0.2 μm filter ; TKN was determined using the standard selenium method (ISO 5663:1984) ; Dissolved organic carbon (DOC) was determined using the standard method (ISO 8245:1999) after samples were passed through a 0.45 μm filter and HCl was added to prevent any further organic matter consumption by bacteria.

3 Results and discussion

Figure 2 presents the WC and DO concentrations at four different depths along the profile (25, 75, 175, 275 cm below soil surface), during 8 flooding and drying cycles of 60 minutes of flooding and 150 minutes of drying (experiment SW150; WC data in a similar manner to Fig.2 for SW240 is presented in the supplementary material). The end of each 60-minutes long flooding period is indicated by the 8 peaks of the surface head in each cycle (Fig.2a). It is important to note that the soil surface is covered by water for longer than the 60 minutes of flooding - roughly 140 minutes in each cycle, which means the time where the soil surface is exposed to the atmosphere is roughly 70 minutes. In the second stage of this experiment (i.e SW240), where DP were 240 minutes, soil surface was actually exposed to the atmosphere for ∼160 minutes during each cycle (see supplementary material). Water front progression through the profile can be retraced by timing the first WC increase following the first FP ~~At a depth of 25 cm, WC initial increase occurred less than a minute after the beginning of the first FP, while at depths of 75, 175 and 275 cm, it occurred after ∼22,∼53 and ∼90 minutes, respectively. This~~ and as reflected by Fig.2, it indicates that flow rate decreased during the first few minutes of the experiment (as should be expected following classic infiltration theory; e.g. Green and Ampt model) but stayed relatively constant as the experiment progressed. WC patterns were significantly different between the various depths - while at a depth of 25 cm WC values ranged between 20.5% and 31.2%, at a depth of 275 cm below the surface, the maximal WC was 18.4% and it dropped below 12% following each DP. Haaken et al. (2016) followed WC patterns in one of the SHAFDAN's infiltration ponds using electrical imaging. While their work is in the field scale, differences in WC between different depths of the profile agree with our findings (Haaken et al., 2016).

DO concentrations also displayed different patterns at different depths of the profile (Fig.2). In the upper parts of the profile (25 cm depth), DO concentration increased in response to each of the DP. In each cycle, the drop in WC caused by the beginning of the DP led to recovery of the DO concentrations and ultimately to complete DO saturation (Fig.2b). As observed in multiple studies in laboratory and field work, close to the surface, DO concentrations are expected to increase in response to the soil aeration during the DP (Mienis et al., 2018; Miller et al., 2006) since regardless of the oxygen movement mechanism (diffusion, advection or convection), the short distance ensures fast response of the system.

At 75 cm depth (Fig.2c), while DO recovery is still observed in response to the beginning of DP, aeration is much less effective and DO concentration averages (through the 8 cycles) dropped by ~ 2.68 mg/L. During the two first cycles, DO concentrations remained almost constant and close to saturation, but upon the beginning of the third FP, a significant decrease was observed. This decrease resulted in a 25% drop in DO concentration following all the next DP. After this initial drop, however, DO patterns and amplitude (following each DP) were sustained through the remaining cycles.

In the deeper parts of the column (Figs.2d and 2e), DP induced DO recovery to a much smaller extent. DO concentrations were able to remain relatively high and constant through the first three cycles, likely due to lower nutrient consumption rates by bacteria at these depths, compared to the upper parts of the profile (Quanrud et al., 1996). Note that DO drop at those depths is a bit hindered, compared to the upper layers. However, as the experiment progressed, DO concentrations decreased steadily to almost complete depletion. These results are to be expected in light of previous laboratory and field observations that demonstrated a decline in DO concentrations with depth (Miller et al., 2006; Orgad et al., 2017). Moreover, DO concentrations along a SAT system's profile are affected by both air movement patterns through the profile during the DP and the consumption of oxygen by bacteria. Since bacterial activity was previously shown to remain relatively unchanged during desiccation(Roberson et al., 1992; Zhang et al., 2012), DO recovery is highly dependent on oxygen transport mechanisms during the DP. These advective and diffusive processes depend on exposure of the surface to the atmosphere, but it also depends on path that air has to pass through, which is longer for greater depths.

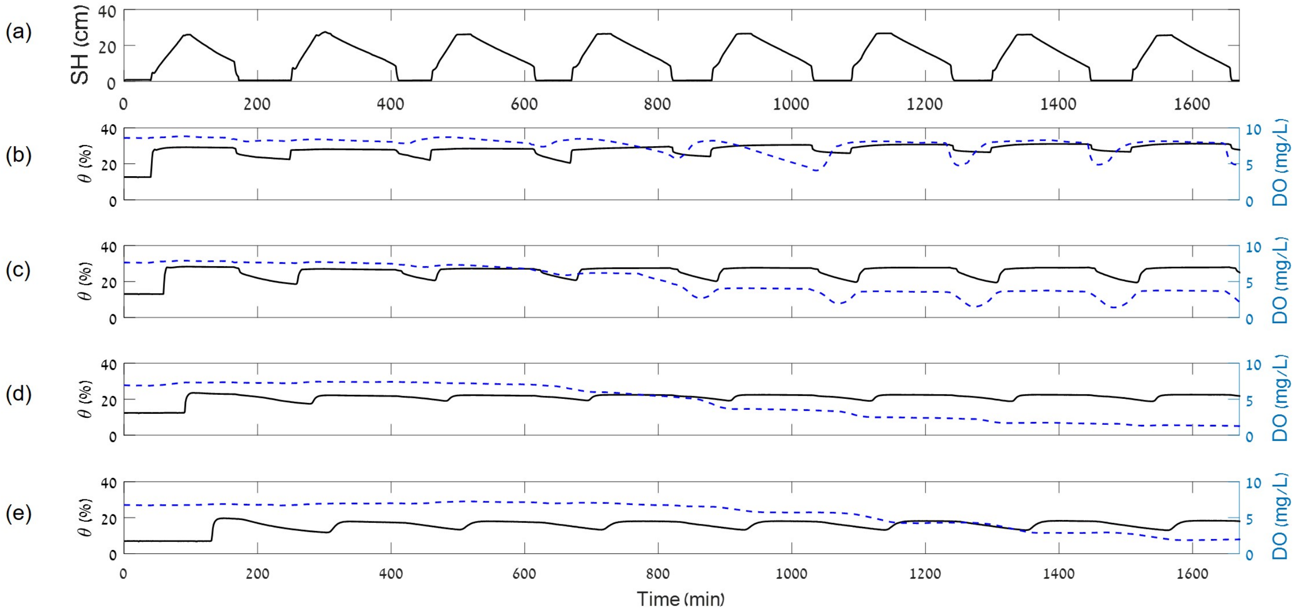

Figure 2. Surface head (SH; 2a), water content (θ) and DO over time at depths of : 25, 75, 175 and 275 cm below soil surface (2b-2e respectively) during SW150

As reflected by the results of SW150 (Fig.2), the 150-minute DP resulted in significant DO depletion in depths greater than 75 cm. To examine the effect of a change in hydraulic operation (longer DP), we increased the length of the DP to 240 minutes (60% increase) after the 10th cycle. Figure 3 presents the DO concentrations at four different depths in the soil profile through the two-stage flooding-drying campaign (experiments SW150 and SW240). By increasing the DP, we increased the time of soil surface's exposure to the atmosphere to $\sim$ 160 minutes on average (compared to $\sim$ 70 minutes on average for SW150) and thus expected to observe increased aeration and some recovery of DO concentrations deeper than 75 cm (where the shorter DP led to almost full DO depletion). During SW240, WC values at a depth of 75 cm below the surface ranged between $\sim$18% and $\sim$12% (compared to $\sim$27% and $\sim$17% for SW150) . At depths of 175 and 275 cm below ground surface, maximal WC were $\sim$ 22 and 18 %, respectively, and minimal WC were $\sim$ 16 and 11 % respectively. At 75 cm depth, shortly following the first longer DP ($\sim$ 100 minutes), DO concentrations increased by $\sim$60% and reached an average of $\sim$ 6.4 mg/L following each of the next DP (compared to an average of $\sim$ 3.7 mg/L during the shorter DP, after the initial drop around the third cycle). In the deeper parts of the profile, a delayed, moderate yet significant response to the increase in DP was observed. The delay in response time compared to the DO recovery in the upper most part of the profile, increased with depth, corresponding to the expected dynamics of air and oxygen movement through the soil profile (DO recovery was observed after around 2,700 minutes for 375 cm and 3,700 minutes for 575 cm). The minimum DO concentrations recorded through the two-stage experiment averaged 0.79, 1.32 and 1.62 mg/L for depths of 175, 375 and 575 cm, respectively . These ranges of DO concentrations below 1.5 meters underground are found in many SAT sites around the world (Amy et al., 2007) and explain the negligible aerobic bacteria activity found under these conditions.

Following each of the longer DP, DO concentrations in the 175 cm sensor fluctuated periodically in response to the wetting and drying periods and reached 4.1 mg/L following the drying events. In the two deepest sensors, DO concentrations stabilized ~~around~~ $\sim$ 3.9 mg/L in the 375 cm sensor and $\sim$ 3.25 mg/L in the 575 cm sensor. Considering the fact that sustaining the shorter DP of SW150 would result in total DO depletion $\sim$ 175 cm depth (supplementary material), these are very important observations. Clearly, too short DP will lead to reducing conditions, at some depth, which as a consequence may lead to insufficient degradation of residual DOC, nitrogen species, and possible leaching of undesired minerals and compounds, such as manganese to the deep vadose zone and the aquifer (Goren et al., 2012) . In addition, the prominent increase in DO in the deeper parts of the profile indicate that longer DP means not only enhanced oxidizing conditions at a given depth, but also increase of the profile volume that did not develop anoxic or anaerobic conditions over the flooding and drying cycles.

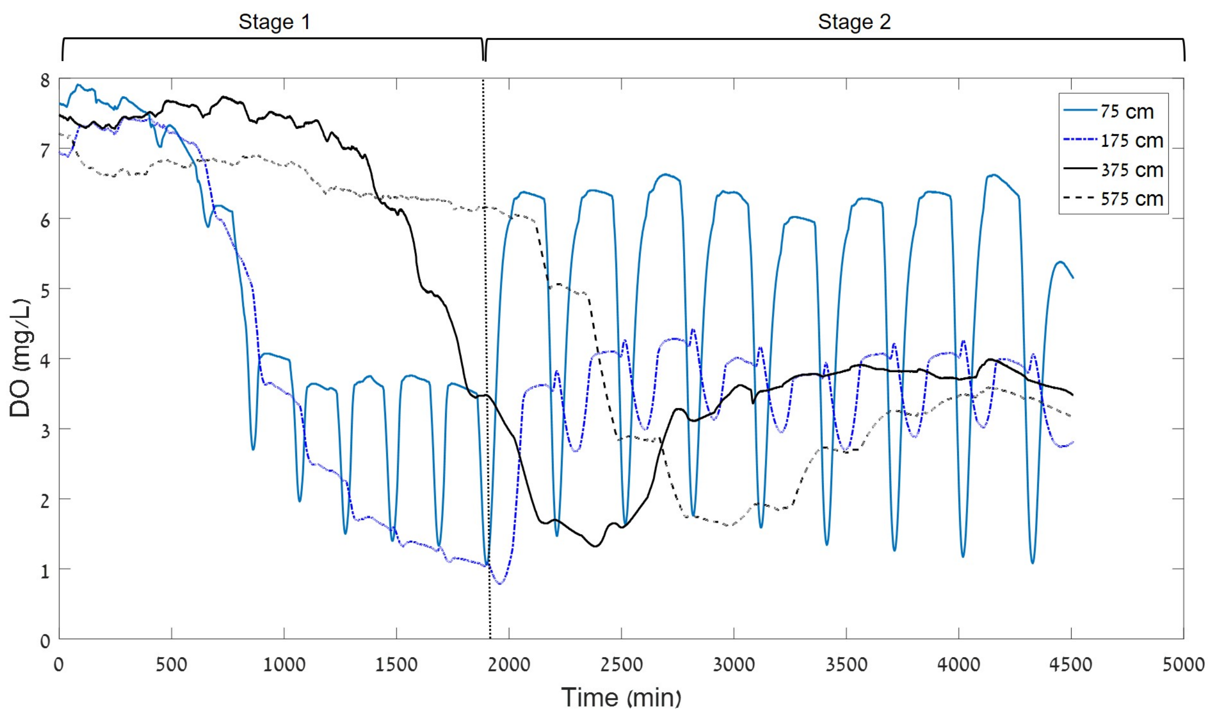

Figure 3. DO concentrations at depths of 75, 175, 275 and 575 cm in response to the increase in DP (between SW150 and SW240). Note the convergence of the deep sensors to < 2 mg/l during the short DP versus convergence to > 3 mg/l in response to the longer DP.

Experiments RW150 and RW240 were designed to further examine the effect of the difference in DP duration on the biogeochemical state of the profile and its effect on some water quality parameters. In these experiments we used real TWW, collected from the Dresden wastewater treatment plant (WWTP) after the activated sludge process. Similarly to what we observed observed in SW150 and SW240, longer drying periods had an advantage in terms of DO concentrations along the profile (not shown). ORP measurements in the upper parts of the column (75 cm) revealed that ORP was significantly higher during RW240, ranging between $\sim$ +400 and $\sim$ +160 mV compared to RW150, during which ORP was mostly negative and reached values as low as $\sim$ -530 mV (supplementary material).

Figure 4 presents $NH_4^+ - N$, $NO_3^- - N$, DOC and TKN and concentrations at the outflow (i.e. 6 meters below soil surface), comparing the results for RW150 and RW240. Outflow $NH_4^+ - N$, TKN and DOC concentrations during RW240 ($\sim$ 0.033, $\sim$ 0.62 and $\sim$ 1.65 mg/L respectively) were significantly lower compared to their inflow concentrations . During RW150, $NH_4^+ - N$, TKN and DOC outflow concentrations ($\sim$ 0.5, $\sim$ 3.8 and $\sim$ 4.4 mg/L, respectively) were also lower compared to the inflow, but averaged significantly higher compared to RW240 (t-test, α=0.05) , suggesting that the longer DP had a significant positive effect on the outflow quality.

During RW150, $NH_4^+ - N$ concentrations were $\sim$ 0.1 mg/L after $\sim$ 400 minutes from the beginning of the experiment but increased noticeably in the following samples (taken after $\sim$ 1500 minutes) while $NO_3^- - N$ concentrations decreased correspondingly. Considering the DO concentrations recorded during the experiment, this observation is to be expected. Progressively decreasing DO levels were observed at all depths greater than 75 cm starting after $\sim$ 850 minutes from the beginning of the experiment (see DO data for depths of 175 and 275 cm in the supplementary material). This suggest that the DO depletion caused by restricted aeration for this duration of time, led to decreased rates of nitrogen species' oxidation, which may explains the increase in $NH_4^+ - N$ concentrations at the outflow after $\sim$1500 minutes. However, looking at the TKN analysis for this experiment, we found that TKN did not significantly increase, suggesting that the increase in $NH_4^+ - N$ concentrations occurred simultaneously to a decrease in organic nitrogen concentrations. This behavior may theoretically be attributed to increased rates of ammonification. However, ammonifying bacteria populations have been shown to thrive under DO saturation (Ruan et al., 2009), which makes this possibility unlikely. Since this study did not include microbial identification, further investigation is needed in order to reveal the exact nature of this observation.

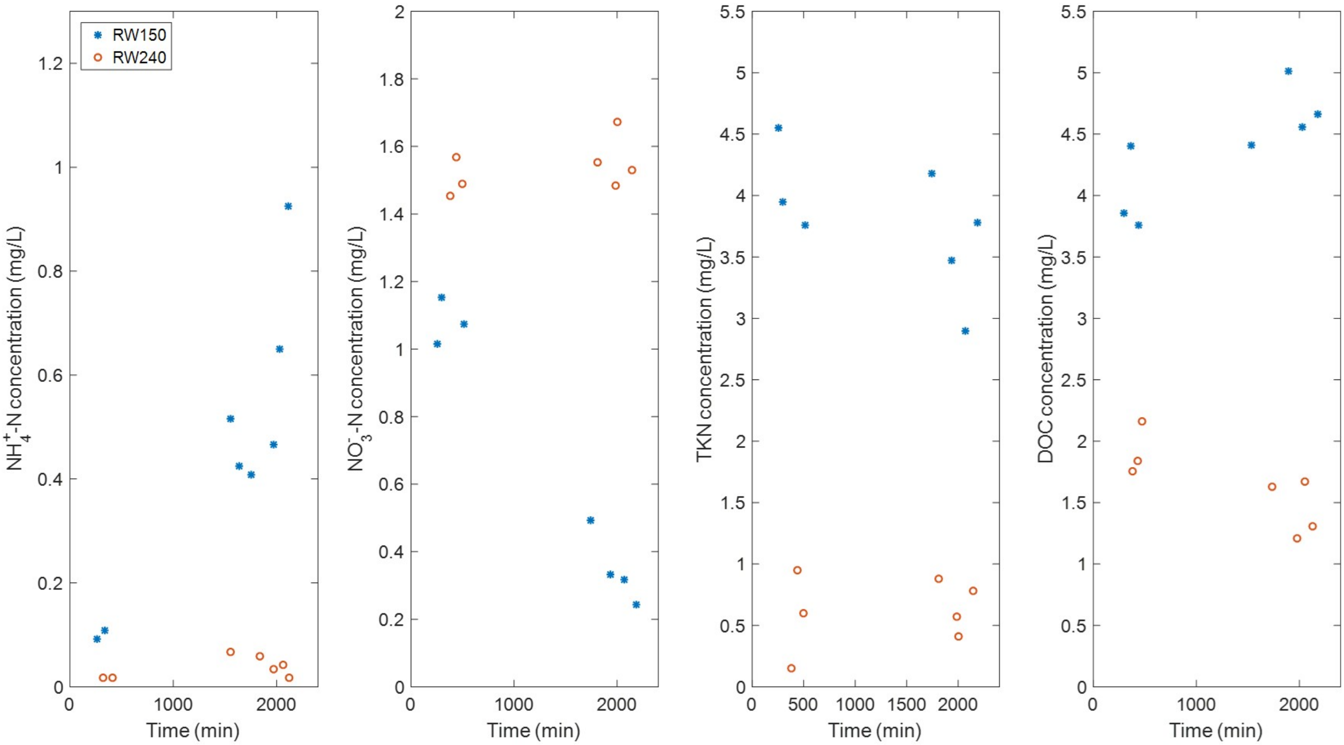

Figure 4. Outflow concentrations of $NH_4^+ - N$, $NO_3^- - N$, TKN and DOC (mg/L) , during shorter (blue) and longer (red) DP (experiments RW150 and RW240 respectively)

3.1 Comparison with field observations

In a field study conducted in the Israeli SHAFDAN site in 2015-2016, Orgad et al. (2017) recorded ORP values along the wetting and drying cycles in a series of flooding and drying campaigns over a year. A description of the site operation and characteristics is brought by Orgad (2017), Idelovitch et al. (2003), Icekson et al. (2011) and others. Figure 5a presents the maximal ORP values in these campaigns at a depth of 95 cm below the pond's surface, around 20 m south-east of the inlet. The ensemble of wetting-drying cycles over an entire year assures a wide variety of wetting and drying proportions. The recorded data showed that when DP were $\sim$15 hours or longer, the maximal ORP values consistently indicated aerobic conditions (and reached $\sim$ + 650 mV).

Figure 5b presents the same relationship for the column experiments presented above. Despite the major differences in time scales (order of 2-4 hours for column experiments vs. order of 15 hours for field conditions), TWW composition as well as system's structure and characteristics between our 1D system and a 3D full scale SAT site, our measurements (WC, DO, ORP) qualitatively agree with the field observations. That is, longer DP led to higher (oxidizing) ORP values, while shorter DP led to lower ORP values (reducing conditions). Comparing the ORP values between the field and the column results (Figs.5a and 5b), it is clear that there is a non-negligible difference - while ORP values never exceeded +440 mV in the column experiment, values of ∼ +700 mV were observed in the field. Moreover, minimal ORP values did not drop below ∼ +100 mV in the field while in the column, negative values of ∼ -150 mV were observed. These differences probably stem from the fact that in the column, a 1D system, air (and water) flow only along the vertical direction while in the field, air flows through the soil profile in all directions and thus allow overall enhanced aeration. Further, in the field the infiltration pond is filled from a single inlet, which means it takes about 10 hours for full surface coverage of the pond. This suggests that further from the inlet, lateral air-flow is possible even hours after the initial flooding.

The difference in time scales between the column and the field experiments may also suggest a difference in the proportions of the air supply mechanisms to different layers of the subsurface. Mizrahi et al. (2016) have suggested that air (in the gas phase) may be "pushed" downwards once the soil surface is fully flooded by water . While this phenomenon is likely maximized in a column experiment (as the soil-air has no time and no horizontal pathway to be released), this mechanism and its impact were not investigated here. However, it is likely that in field conditions, where lateral air movement is allowed, this mechanism of air supply is of lesser significance, and air movement due to diffusion or air-pressure gradients becomes more dominant.

Interestingly, it is evident from the field data (Fig.5a) that very long DP (>20 hours) did not present an advantage over DP of moderate duration (between 15 and 20 hours), at least at a depth of 95 cm. Considering the common understanding that most of the biochemical degradation of organic matter at the SHAFDAN SAT site happens at the upper meter or so (Quanrud et al., 1996), DP of more than 15-20 hours seem to have no influence on the oxidation state of the profile. In light of the understanding that longer DP lead not only to increased aeration but also to an increase of the aerobic volume of the soil profile,

a combination of longer FP and sufficiently long DP (such that allow this profile aerobic volume increase) may be beneficial for both amounts of TWW that the site is able to treat per unit time as well as reclaimed water quality.

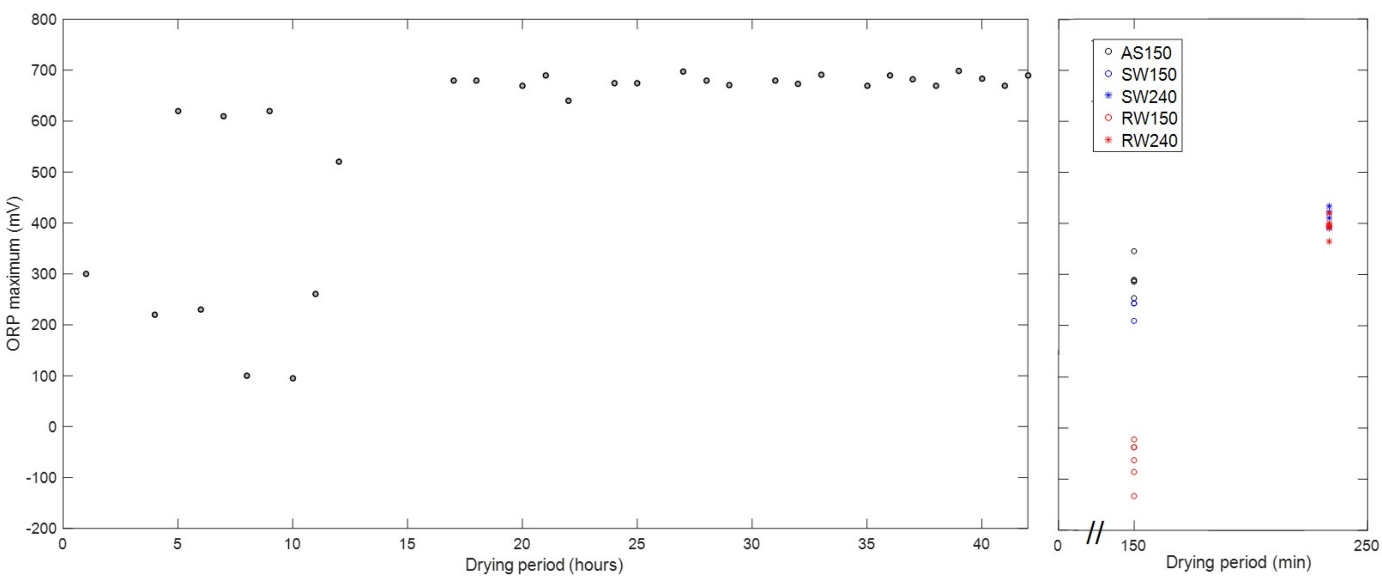

Figure 5. Maximal OPR values versus DP length a) during field infiltration campaigns in the SHAFDAN site (at 95 cm depth) and b) during the column experiments AS, SW150/240, RW150 and RW240

As described in Table 1, two of the four experiments presented in this work (RW150 and RW240) included real TWW while in the two earlier experiments synthetic TWW were used. To allow comparison between the experiments, their inflow DOC, TKN and $NH_4^+ - N$ concentrations were matched (see supplementary material) so that the main difference between the two WW sources stems almost entirely from their microbial content (likely there are some differences in micro-nutrients as well). Compared to tap water-based inflow that contained very low concentrations of bacteria, the real TWW collected from the Dresden WWTP had gone through an activated sludge reactor but were not disinfected. Hence, it contained much larger quantities of microorganisms. During RW150, we observed lower ORP values compared to SW150 that is identical in terms of FP/DP. The average peak ORP throughout the SW150 were ∼+220 mV while in RW150, the average peak ORP was ∼-80 mV (Fig.5b), despite the fact that the inflow in both experiments contained similar organic loads. Since both RW150 and SW150 had similar DPs, the lower overall ORP values recorded in RW150 suggest that the difference in ORP stems from oxygen consumption rates. Theoretically, difference in oxygen consumption rates may stem from either higher concentrations of bacteria or the presence of less easily degradable organic carbon sources in the WW (compared to glucose). Ak et al. (2013) compared organic carbon degradation and DO concentrations between synthetic and real wastewater infiltration in a series of 120 cm soil column experiments. They found that degradation of organic carbon was more efficient for the synthetic WW which they attributed to the presence of glucose as the main carbon source in the synthetic WW (compared to the less easily biodegradable carbon sources in the real WW). In our experiments, however, the real TWW collected from the Dresden treatment plant had only ∼10 mg/L of organic carbon prior to the addition of glucose (i.e. glucose accounted for >90% of the DOC in the experiments with real TWW). This may suggest that the lower ORP values recorded in RW150 are related to additional oxygen consumption by the microbial community in the influent itself which therefore may be more dominant in the degradation process than commonly perceived.

~~From these results, it is clear that the nature of the secondary treatment, which determines the inflow composition (in terms of inflow bacteria concentrations as well as organic load) affects the biogeochemical state of the SAT system through reactions' rates and scope. Our observations suggests that the contribution of the microbial community in the influent itself is more dominant in the degradation process than commonly perceived. In their review, Sharma et al. (2017) found that recovered TWW's quality in SAT sites around the world varied significantly depending on the inflow source. Removal of DOC, nitrogen species and organic micropollutants was generally better when the pre-treatment was more extensive. Specifically, they found that advanced processes like ozonation, implemented prior to SAT resulted in higher removal efficiency. Since ozonation would generally damage the microbial community in the influent, it seems like the absence of microorganisms in the influent enhances organic matter degradation by soil's native bacteria. However, advanced oxidation processes affect more than the microbial content of the TWW alone and thus, to understand the role of influent microbial community on the biogeochemisrty in SAT systems, further investigation is needed.~~

In field scale SAT systems, clogging is an important issue to consider. Throughout the long-column experiments described here, we did not observe significant indications of physical or biological clogging. This is evident by the consistent patterns of surface head along the flooding and drying cycles. Possibly, this is due to the fact that the experimental setup was not exposed to sunlight and therefore algae development is not expected. However, the development of biofilm has an effect on the hydraulic properties of the unsaturated zone (Volk et al., 2016) and since it has been shown that the organic load of the influent is positively correlated to the phenomenon of bioclogging (Rosenzweig et al., 2014), this will be an important topic to address when dealing with full scale sites.

4 Summary and conclusions

In a series of long column experiments we examined an the expected SAT system response to different hydraulic operation regimes, namely wetting and drying periods. Experiments were conducted using real and simulated synthetic treated wastewater. WC, DO and ORP were monitored along the column, and water samples were collected along the column and at its bottom end, at 6 m at the outlet , and analysed for nitrogen species and DOC. Hydraulic regimes considered were of 60 minutes of wetting, and 150 or 240 minutes of drying (corresponding to ∼140/70 and ∼140/160 minutes of the soil surface being ponded/exposed to the atmosphere, respectively).

As could be expected, shorter drainage periods led to higher WC regimes in the subsurface, and lower DO values. Interestingly, the shorter DP also led to almost complete depletion of the DO throughout the column (below ∼50 cm), and creation of prevailing low ORP values, indication anoxic to reducing conditions throughout most of the column. Longer DP, on the other hand, led to oxidizing conditions throughout the column for most of the time. These conditions are also expressed as column outlet water qualities, where longer DP led to better oxidation of NH_4^+, and reduction of total nitrogen as well as DOC. The almost immediate response of the DO concentrations at depth to the surface exposure time to the atmosphere suggests domination of advective oxygen movement in the gaseous phase (over diffusion in the gaseous phase or advection in the liquid phase). These results suggest that longer DP not only shift the active (oxidizing) part of the system towards oxidizing conditions, but it also makes this region larger. To the best of our knowledge, this is the first work to suggest dependence of the aerated part of the vadoze zone under SAT upon the DP, rather than a simple consideration of higher aeration of a fixed volume close to the surface.

Longer DP have their consequences - on one hand, they led to more oxidizing conditions, and to the extension of the oxidizing parts of the variably saturated zone. On the other hand, they led to reduction in the volumes that can be infiltrated and recharged to the aquifer. Clearly these are contrasting objectives that need to be further explored and optimized for a given site. The qualitative similarity between ORP values in these column experiments and those measured at the SHAFDAN site suggest that these findings are also relevant for real conditions, and that such optimization can be conducted also in reality.

To conclude, our results suggest that the variably saturated zone in a SAT system can and should be seen as a pseudo reactor, in which DO and ORP values can, to a certain extent, be controlled. Longer DP dictate allowed better degradation of NH_4^+, organic nitrogen and organic carbon, but led to reduced infiltration. The immediacy of the DO recovery at depth following sufficient DP may suggest that the ratio between drying and wetting periods is not the parameter that dictates the SAT biogeochemical dynamics, and long enough DP (that is primarily a function of hydraulic properties and desired oxidizing depth) can be followed by much longer wetting periods. This however was not examined, yet.

Author contributions. FB and JS prepared the experimental set up, SBM, AF and NW designed the experiments, OO provided and analysed the field data, SBM preformed the column experiments, analysed the data and prepared the paper with contribution of all authors.

Competing interests. The authors declare that they have no conflict of interests

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Supplementary Material

1 TWW composition

1.1 ~~Synthetic WW preparation~~

~~Table S1 contains the added concentrations of ammonium, asparagine and glucose for the preparation of the synthetic WW. Table S2 describes the ammonium, TKN and DOC content of the synthetic WW.~~

Table S1. ~~Synthetic WW composition (added concentrations)~~

Chemical	Concentration (mg/L)
Ammonium	5
Asparagine	4.5
Glucose	95

Table S2. ~~Synthetic WW chemical composition~~

Analysis	Concentration (mg/L)
Ammonium test	4.9
TKN	9.2
DOC	103

1.2 Real TWW chemical composition

~~Table S3 describes the chemical composition of the TWW collected from the Dresden WWTP . Table S4 describes the final TWW composition after Glucose and Ammonium were added to reach similar composition to the synthetic WW.~~Table S1 describes the chemical composition of the TWW collected from the Dresden WWTP before Glucose and NH_4^+ were added to reach similar composition to the synthetic WW.

Table S3. Real TWW chemical composition (as collected from the Dresden WWTP)

Analysis	Concentration (mg/L)
Ammonium	0.94
TKN	5.2
DOC	10.7

Table S4. ~~Real TWW chemical omposition (after the addition of glucose and ammonium)~~

Analysis	Concentration (mg/L)
Ammonium	4.9
TKN	10.1
DOC	102

2 Soil characterization

Soil from the YAVNE2 pond cluster of the SHAFDAN site was collected. Prior to packing the column, the different layers of the soil were characterized. Particle size distribution , porosity TOC were determined. All soil horizons were found to contain $> 86\%$ of sand with an average porosity of $\sim$0.45. Column was packed according to the layering at the field.

Table S5. Soil characterization: porosity, texture and TOC content

Layer	Top (cm)	Bottom (cm)	Porosity (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	TOC (%)
1	0	153	0.48	0.7	93.9	2.4	3	0.25
2	153	258	0.48	0.6	94.4	2.1	2.9	0.1
3	258	352	0.47	0	99.2	0.1	0.7	0.01
4	352	462	0.42	0	97.4	0.6	2	0.02
5	462	480	-	-	-	-	-	-
6	480	600	0.42	0.4	86.4	5.6	7.6	0.05

3 WC and DO during ~~stage 2 of experiment 2~~ SW240

~~Figure S1 presents the Surface head, WC and DO concentrations recorded during the second stage of experiment 2 (synthetic WW; DP of 240 minutes).~~ Figure S1 presents the Surface head, WC and DO concentrations recorded during SW240.

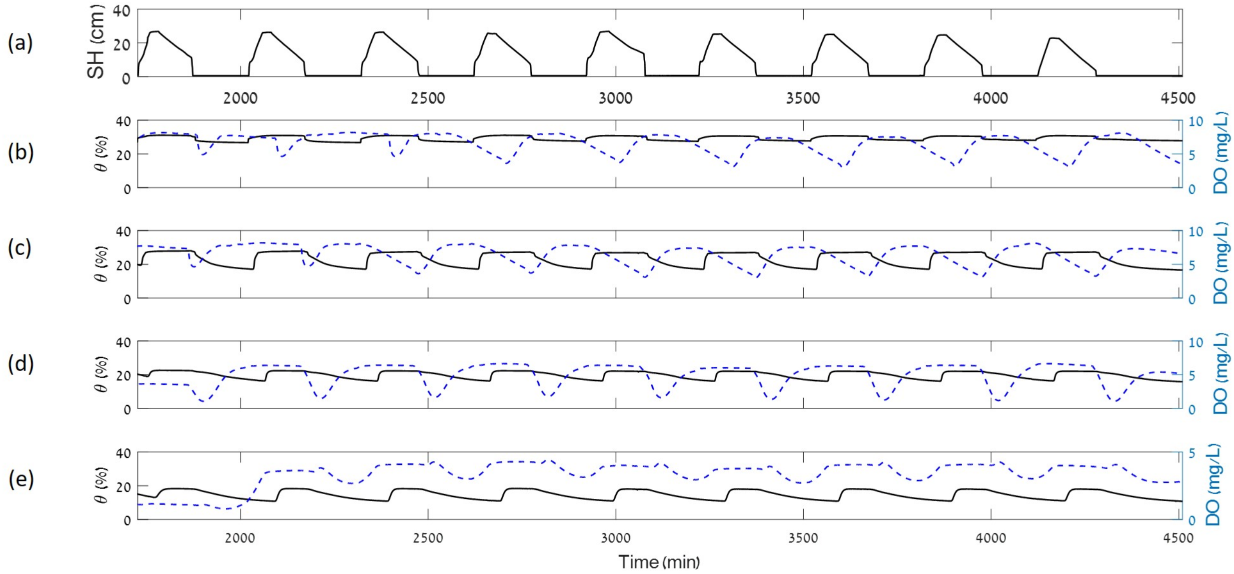

Figure S1. Surface head (SH; S1a), water content (θ) and DO over time at depths of : 25, 75, 175 and 275 cm below soil surface (S1b-S1e respectively) during SW240.

4 DO depletion in a preliminary experiment

In a preliminary experiment, cycles of 60 minutes FP and 150 minutes DP were implemented, using synthetic WW. Figure S2 shows that after $\sim$ 3000 minutes, complete DO depletion was observed at the 175 cm DO sensor.

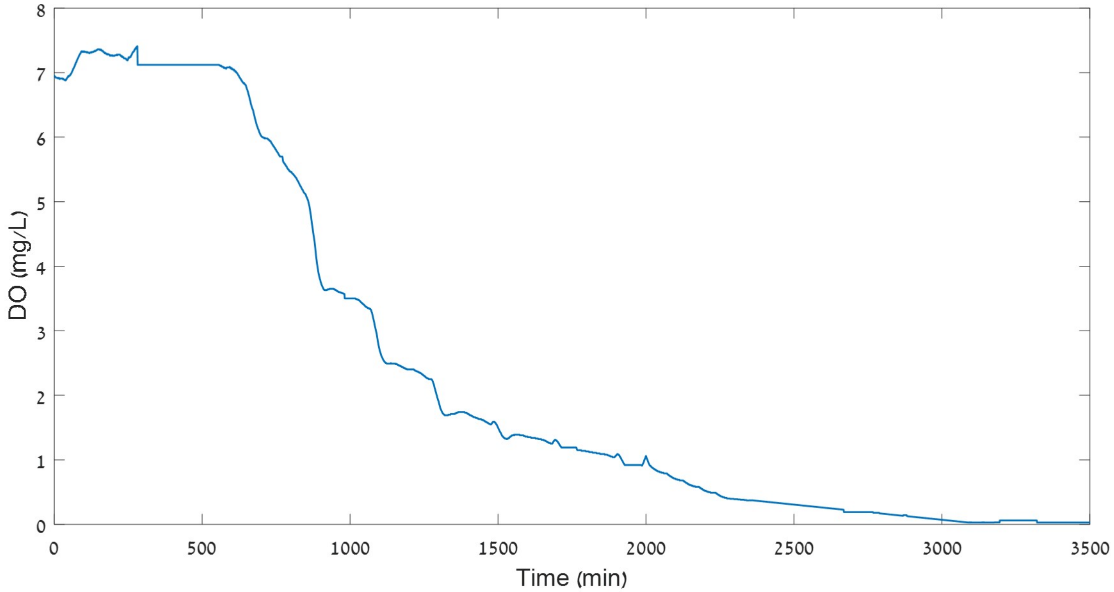

Figure S2. DO concentrations during a preliminary experiment. synthetic WW were used and cycles were of 60 minutes FP and 150 minutes DP

5 ORP during ~~experiments 3 and 4~~ RW150 and RW240 at a depth of 75cm

Figure S3 presents the ORP at a depth of 75 cm recorded during ~~experiments 3 (blue line) and 4 (red line)~~ RW150 (blue line) and RW240 (red line) . These results show that the longer DP had a beneficial effect on the ORP at this depth - in ~~experiment 4~~ RW240 , ORP values were significantly higher compared to ~~experiment 3~~ RW150 , throughout the majority of the experiment, ORP values were greater than 200 mV and reached ∼400 mV periodically, suggesting that the longer DP contributed to enhanced aeration that in turn resulted in higher outflow quality.

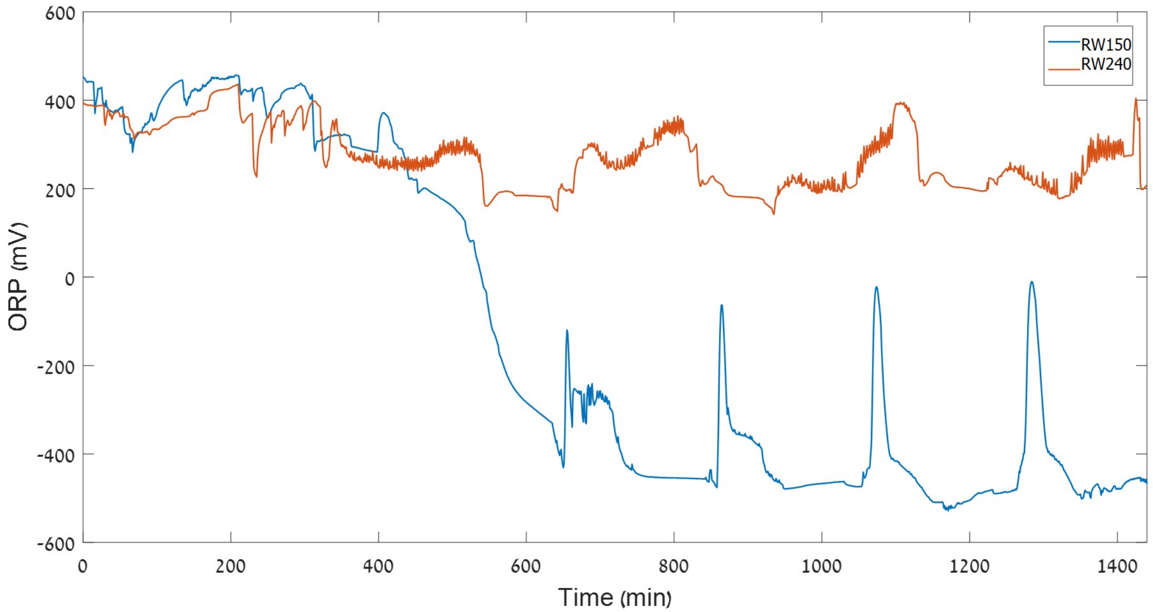

Figure S3. ORP at a 75 cm during ~~experiments 3 (blue line) and 4 (red line)~~ RW150 (blue line) and RW240 (red line)

6 DO concentrations during experiment 3 RW150

Figure S4 shows DO concentrations at depths of 175 and 275 cm recorded during experiment 3 RW150 (shorter, 150 minutes-long DP).DO depletion occurred after ∼850 and ∼1400 minutes from the beginning of the experiment (for 175 and 275 cm respectively).

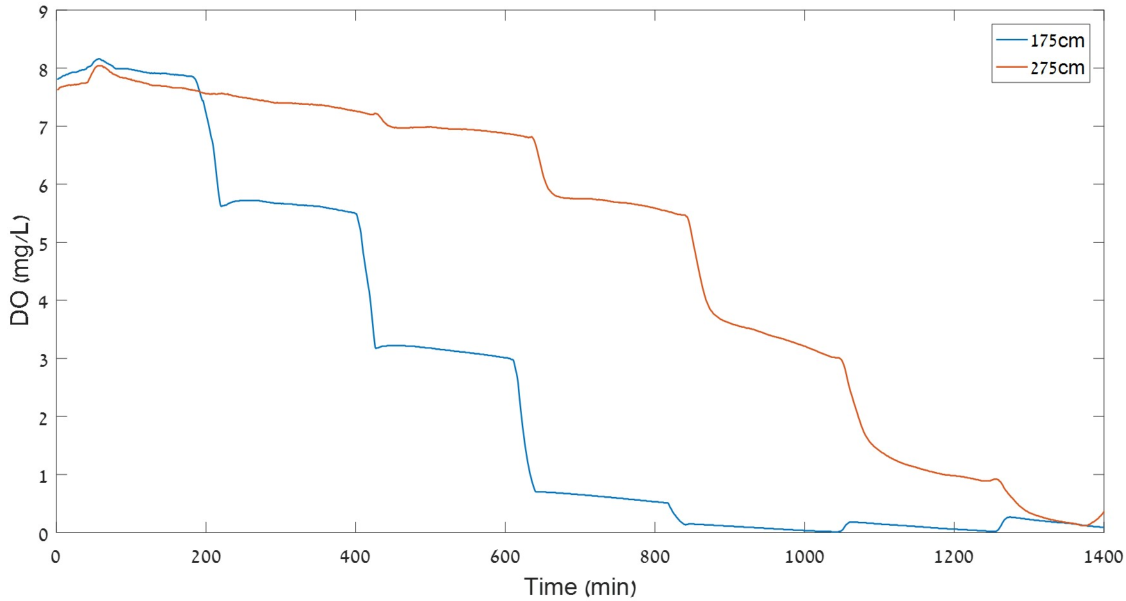

Figure S4. DO concentrations at 175 and 275 cm during experiment 3 RW150

7 ORP and DO values during ~~experiment 2~~ SW150 and SW240

Figure S5 shows DO and ORP concentrations recorded during SW150 and SW240at a depth of 75 cm. A correspondence between the two monitored parameters is observed.

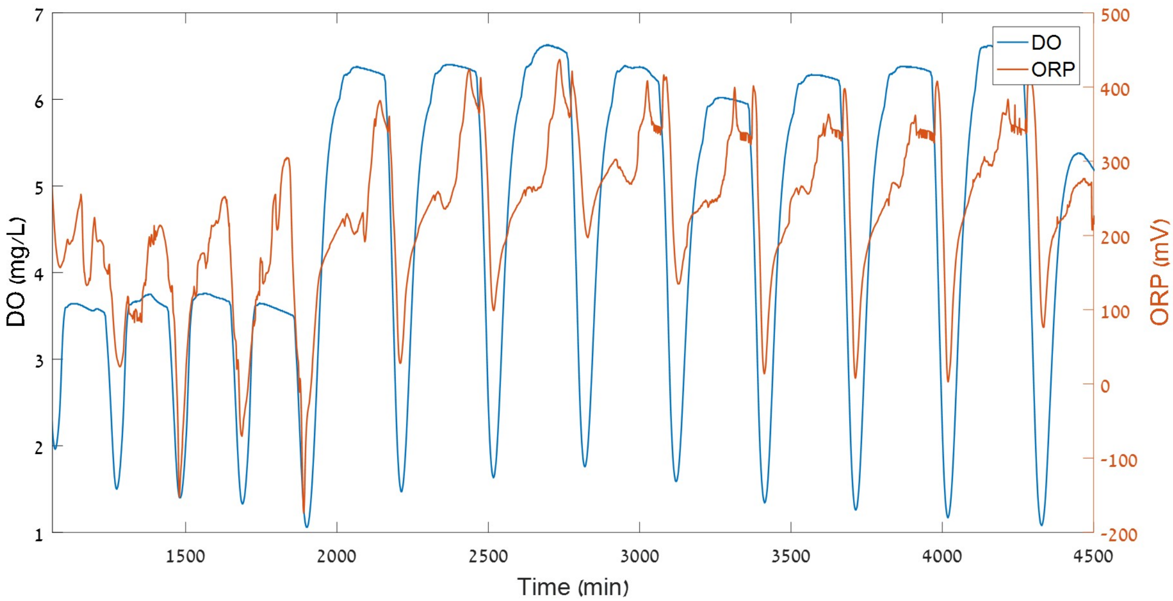

Figure S5. DO and ORP concentrations at 75 cm depth during ~~experiment 2~~ SW150 and SW240

8 The Israeli SHAFDAN SAT site

In Israel, the SHAFDAN site, which is the largest WWTP in the country, treats $\sim$ 150 million m^3 of wastewater originating from the city of Tel Aviv and surrounding municipalities annually. Following the SAT process, the treated water is recovered through recovery wells located 1–2 km away from the infiltration basins, transported to the south of Israel and is used by farmers for crop irrigation. Effluents of the wastewater treatment plant are first treated in the mechanical, biological treatment plant and then recharged into a section of the sandy Israeli coastal aquifer in which the groundwater table lies $\sim$30-40 m below ground surface. Sediments are mainly composed of sand and silty sand from the Kurkar formation. Hydraulic loading in each of the infiltration basins is $\sim$ 80-150 m/y (depending on the basin's capacity). Hydraulic operation is composed of $\sim$24 h flooding periods, and a drainage period of 48–72 h.