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Estimation of limitations for groundwater recharge using the example of the Sarden site in Syria

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Groundwater is the main source of all renewable water resources for drinking and irrigation water in most arid and semi-arid areas. However, groundwater abstraction by pumping has increased in most areas significantly, leading to a lowering of the groundwater level. Managed aquifer recharge is a measure to prevent or counteract these temporary and permanent groundwater declines and their negative effects.

The work described here deals with the numerical simulation of treated wastewater infiltration for improving the local groundwater balance in the catchment area of Sarden village, Syria. The semi-arid region is characterized by shallow silty clay soils, limestone cliffs and karst aquifers. Different model setups were built up by means of the software PCSiWaPro simulating the effects of different boundary conditions on the saturation conditions in the vadose zone. This should enable an initial assessment of whether and under what conditions the installation of an infiltration system is possible.

Results of the research are showing that the hydraulic conditions in the unsaturated soil zone at the site are influenced most by the groundwater level and the number of trenches used for infiltration, whereas precipitation events are playing a subordinate role. In case of elevated groundwater level and too low number of infiltration trenches, the water can rise up to or in the infiltration trenches.

KEY WORDS: recharge of groundwater, treated wastewater infiltration, infiltration trenches, numerical model

Introduction

At present, an increasing water scarcity in different parts of the world is observed caused by rapid population growth and the consequences of climate change. The supply of freshwater from groundwater and surface water sources is limited and cannot meet the growing demand (Food and Agriculture Organization of the United Nations, 2018; Gleeson et al., 2012; Wada et al., 2010; Yaghi et al., 2016). Furthermore, discharge of urban sewage, the missing sewage network and generally poor living conditions have led to a deterioration in surface and groundwater quality in many developing countries (Wild et al., 2007).

Also in the semi-arid country Syria, high population growth and accelerated urbanization have increased the demand for water and led to a continuous depletion of water resources, which endangers their long-term sustainability (Berndtsson and Mourad, 2012). The results of a study in north Syria, Sarden region showed that groundwater pumping leads to a long-term decrease in groundwater levels, particularly in the dry season (Bananah, 2016).

In this case, managed aquifer recharge or artificial groundwater recharge (MAR) can be used to prevent or counteract temporary and permanent water scarcity problems by infiltrating excess surface waters (Casanova et al., 2016; Dillon et al., 2009). One opportunity here is the use of wastewater treated by preliminary treatment stage. The following infiltration of this water in the course of recharge can reduce the pressure on freshwater resources, such as groundwater, especially in arid and semi-arid areas (Bouwer, 2002; Dillon et al., 2009; Heidarpour et al., 2007).

At the moment, however, large amounts of untreated or inadequately treated wastewater are used in developing countries by farmers for irrigation, which raises concerns about public health and the environment. This situation requires rethinking the way wastewater has to be treated and reused (Manzoor, 2007; Scheffer et al., 2003). Especially in areas where the construction of a sewage collection system is not considered economically viable, reuse of water treated by decentralized treatment systems for infiltration can be an option. 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. The decentralized wastewater treatment and disposal for rural regions has been already studied, e.g., in the Kingdom of Jordan (Van Afferden et al., 2015) and many other areas worldwide (Händel et al., 2018).

These sustainable decentralized treatment systems are focusing on the on-site treatment and recycling of resources contained in domestic wastewater (Capodaglio et al., 2017). For the following reuse of treated wastewater various techniques are used (Asano and Cotruvo, 2004). On the one hand, the discharge of treated wastewater occurs into surface waters, such as rivers or streams. On the other hand, the disposal of the treated wastewater effluent takes place by direct infiltration into the soil by means of infiltration elements such as soakaways, trenches, drainage pipes or swales (Sieker, 1998; Shuster et al., 2010). Here, the quality of treated wastewater effluent can be improved before reaching the aquifer by the processes of filtration, absorption and biodegradation in the aerated unsaturated soil zone (Martins et al., 2017; Morales et al., 2016; Nema et al., 2001, Reemtsma et al., 2000; Zhang et al., 2007). However, using the treated wastewater harbours risks, because pollutants can reach the aquifer (Bekele et al., 2018; Burger and Čelková, 2005).

For the planning and dimensioning of such infiltration systems, it is necessary to understand the taking place processes below the infiltration system depending on the geohydraulic properties of the unsaturated and saturated parts of the aquifer as well as operational parameters of the system such as infiltration rates or the infiltration cycle (Alam et al. 2021; Bouwer, 2002; Lyman et al., 1992; Meikle et al., 1995). Especially, the variation of water saturation respectively the aeration in the subsurface zone is of particular importance due to its importance for the purification of the infiltrated water. Optimal conditions can be ensured by avoiding fully saturated conditions in the soil below the infiltration system.

Numerical models can be used to take a closer look at these processes and to assess the influence of different boundary conditions on the hydraulic conditions below the infiltration system (Krug, 2001). Therefore, a large number of scenarios with different boundary conditions for the Sarden site were performed to eliminate some uncertainties regarding the future use of treated wastewater for the application of artificial groundwater recharge.

The results of the study should provide answers to the following questions:

- Is the Sarden site suitable for infiltrating treated wastewater by trenches in terms of quantity?
- How are the hydraulic conditions below the infiltration system influenced by the boundary conditions groundwater level, precipitation and the number of trenches?
- How does the infiltration influence the saturation of the vadose zone below the infiltration system?
- Is the infiltration influencing the groundwater level?

Material and methods

Study area

The study area "Sarden plain" is located in a catchment area covering around 44 km^2, whereby the "Sarden plain" itself covers an area of approx. 7 km². It is located in a semi-arid area in north-western Syria (50 km west of Aleppo) between 36° 06'–36° 11' latitude and 36° 33'–36° 38' longitude and represents a secondary catchment area of the Orontes Basin (Fig. 1). According to topographic reliefs, the highest elevation in the basin is 825 m above sea level, the lowest point is at 437 m above sea level. The climate is semi-arid/Mediterranean with hot, dry summers and cool, humid winters (Farahani et al., 2009). The precipitation varies between 290 mm per year in dry years and 750 mm per year in wet years and 564 mm per year as the mean precipitation, which begins in October and extends to April. The potential evapotranspiration is between 1200 mm per year and 1800 mm per year. The natural infiltration rate in the catchment area was estimated at 55% of the average annual precipitation, which corresponds to an annual value of 310 mm (Bananah, 2016).

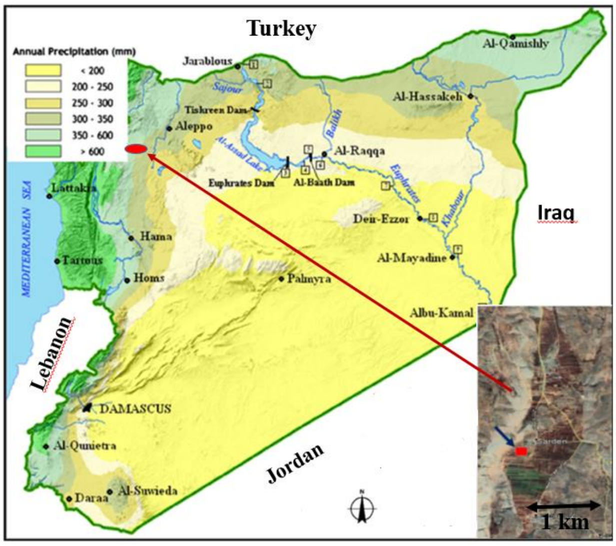

Fig. 1. Study area of the Sarden Plain (Google, 2022).

The dominant type of geological formations in the study area is the Neogene including the middle Helvetians, composed of biogenic sediments along with limestone rocks (Abbas et al., 2015; Brew et al., 2001). The upper soil layer consists of loamy-silt soil and is poor in organic matter (Bananah 2016).

There are three villages in the Sarden plain with a total of about 3600 inhabitants. The village of Sarden, located in the middle of the plain, was chosen as the location for the study. Around 500 people are living permanently in the village. However, in summer (June to August), the population temporarily increases to around 900 people. At the moment, there is no effective wastewater treatment plant in the three villages. However, groundwater recharge by using treated wastewater could be a final step in solving the problems regarding the quantity and quality of water in the Sarden plain.

Numerical investigation

Simulation program PCSiWaPro

The realized simulations were carried out with the help of the simulation software PCSiWaPro, developed at the Technical University of Dresden, Institute for Waste Management and Contaminated Sites Treatment (Gräber et al., 2006). The program is based on the SWMS-2D program, developed by Šimůnek and van Genuchten (1994). The program is accordingly applicable to problems in variably saturated porous media, i.e. under unsaturated to fully saturated conditions. Two-dimensional models can be realized, by applying Richards-equation (Richards, 1931) for unsaturated flow and Mualem-van-Genuchten retention and relative hydraulic conductivity model (Mualem, 1976; Schaap and van Genuchten, 2006).

Model setup

A two-dimensional numerical model with the dimensions of 80.2 m (width) and 30 m (height) was built up for simulating the quantities of treated wastewater and precipitation to be potentially infiltrated in the future (Fig. 2). The cross-section of the trenches and the saturated and unsaturated soil zone is represented by 42,500 nodes in total. Discretization is carried out using the finite element method, with irregular triangular structures being used in the areas with the high pressure gradients to be expected and geometric discontinuities (e.g. trench area) are designed with a correspondingly close mesh.

The thickness of the aquifer is assumed with 30 m. The groundwater level is set at 10 m below ground surface (GWL10m) in a first variant, in another variant the groundwater level is set at 6 m below ground surface (GWL6m).

For the infiltration of the water, 8 infiltration trenches were implemented in the first variant (Fig. 2a), in another variant the infiltration was carried out by means of 17 infiltration trenches (Fig. 2c). The distance between the trenches is 5 m in the model with 8 trenches and 2.5 m for the model with 17 trenches. The height of the trenches is set at 0.5 m and the width at 0.6 m. The model boundary was defined based on estimates of the transverse distribution of the water flow respectively the range of the infiltration front. Thus, the distance between the outer trenches and the boundary of the model is 20.2 m in the system with 8 trenches and 15 m in the system with 17 trenches.

The inflow of treated wastewater and precipitation to the trenches is defined as a boundary condition of the second type with a time-dependent, variable inflow. The area between and around the trenches was also provided with a boundary condition of the second type, only precipitation infiltrates here. The lower border of the model representing the boundary to an impermeable storage layer as well as the lateral borders above the saturated zone are defined as no-flow boundary condition. The outflow from the model is regulated at the left and right border by a boundary condition of the first type.

The amount of treated wastewater to be infiltrated by means of trenches is 80 litres per inhabitant and day, which results is 40,000 l/d for 500 people (September to May) and 72,000 l/d for 900 people (June to August). The simulated period is 365 days in total, which includes the periods of low and high treated wastewater accumulation. The distribution of these volumes over the day occurred according to the hydrograph of the daily water consumption (DIN EN 12566-3, Deutsches Institut für Normung e.V., 2016). The infiltration of the resulting treated wastewater sum in the model was realized every 6 hours, which corresponds to the time step intervals of the model. Thus, a realistic infiltration pattern with increased wastewater accumulation in the morning and evening hours of a day was realized. The precipitation infiltration was implemented as a variable, time-dependent flux boundary condition using the precipitation hydrographs of years with average annual precipitation (560 mm) and years with high precipitation (750 mm) (Syrian Ministry of Agriculture and Agrarian Reforms, 2013).

An evaluation of the infiltration process taking into account the different boundary conditions should be carried out based on the simulated water contents in the implemented observation points and based on the groundwater levels. Therefore, 14 observation points for the model with 8 infiltration trenches and 21 observation points for the model with 17 infiltration trenches were implemented (Fig. 2b and 2d).

The specific soil hydraulic parameters from on-site measurements were not available. Based on large-scale geological maps, it was defined that the upper soil zone consists of loamy silt. The entire soil zone, except the area around the trenches, is assumed to be a homogeneous, isotropic layer with a saturated hydraulic conductivity of around 5×10^{-6} m s^{-1}. The material around the trenches is defined as coarse sand with a hydraulic conductivity of around 2.5×10^{-4} m s^{-1}. The retention parameters of the soils are assumed according to DIN 4220, Deutsches Institut für Normung e.V., 2008 (Table 1).

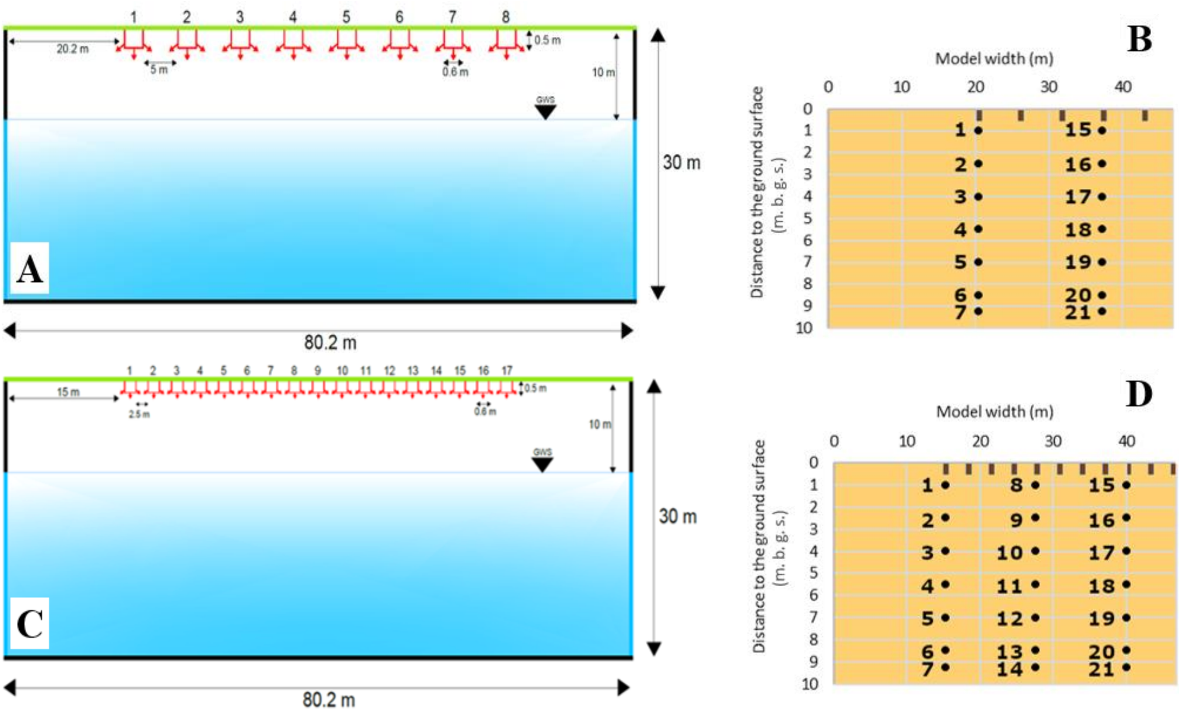

Fig. 2. Conceptual model of the infiltration systems with 8 trenches (a) and 17 trenches (b) for the Sarden site; location of the observation points (MP) in the cross-section of the model below 8 trenches (c) and 17 trenches (d).

Table 1. Hydraulic parameters of the used soil materials

	Aquifer	Area around the trench
Saturated hydraulic conductivity K [m s^{-1}]	5 x 10^{-6}	2.5 x 10^{-4}
Residual water content Θ_r [m³ m^{-3}]	0.05	0.0
Saturated water content Θ_s [m³ m^{-3}]	0.40	0.38
van Genuchten shape parameter n [-]	1.35	1.47
van Genuchten shape parameter a [m^{-1}]	1.70	22.1

The simulation results were first fundamentally checked for plausibility using the information on numerical stability (balance error, iterations per time step) supported by the PCSiWaPro program.

Results and discussion

General insights

Parameter adjustments within different scenarios can lead to significant changes in the simulated water content. During the evaluation, however, it was possible to obtain findings, which apply independently of the simulation variants considered.

All determined water content curves can be divided into four phases (Fig. 3a and 3b). In the short first phase, the short-term settling process of the numerical model can be observed. In the second phase, which begins within the first month November and lasts until the end of May, changes in the water content are caused by the infiltration of water from precipitation events instead of by the inflow of treated wastewater. In the third phase (June to August) the water content is significantly increasing and remaining at a constant level due to the higher inflow of treated wastewater caused by the higher number of inhabitants in summer. Phase four (September to October) shows the same behaviour as phase two.

With the displayed water contents at observation point 15 (Fig. 3a), which is located directly below the central infiltration trench, for the two chosen scenarios in Fig. 3a (8 trenches, GWL6m, increased annual precipitation/17 trenches, GWL10m, average annual precipitation) the full range of water content values and the biggest discrepancy in the water content curves for all scenarios are visualized.

When looking at the groundwater level below the trenches (Fig. 3c), it becomes clear that not only the water content at the observation points increases as a result of the treated wastewater infiltration. By comparing the groundwater levels in the time with reduced (end of May, runtime 211 days) as well as

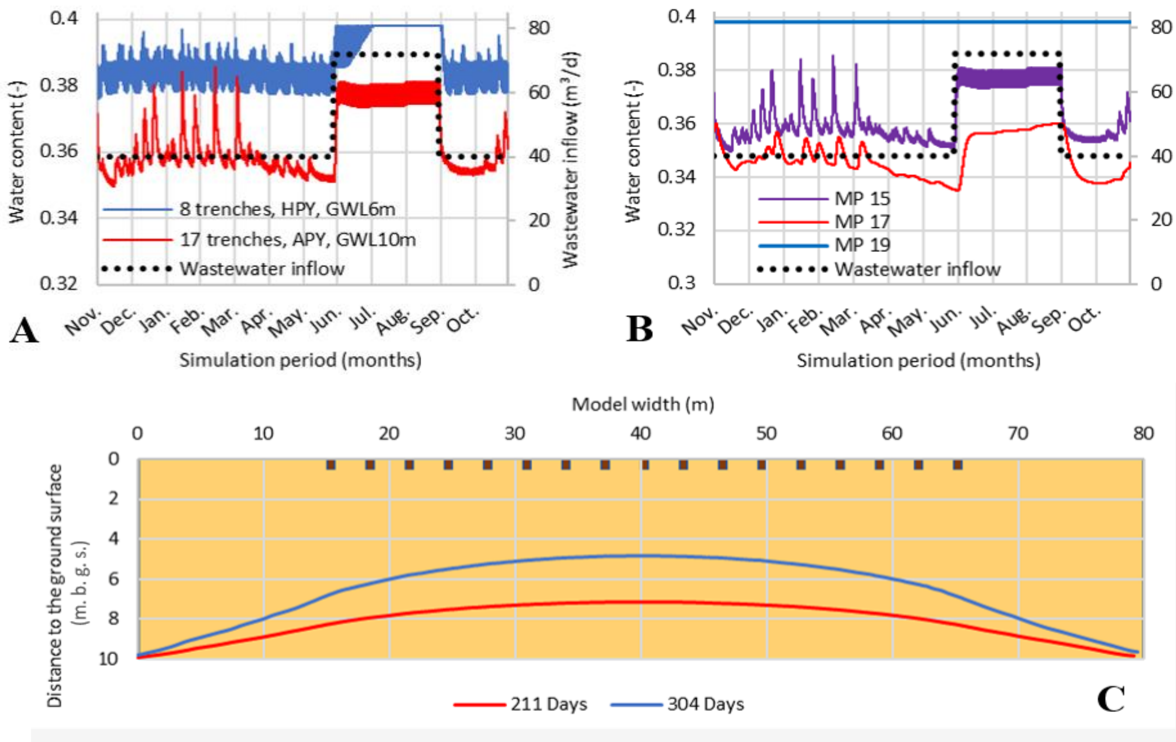

Fig. 3. Water content at observation point 15 for two different scenarios with best and worst-case conditions (a); water content at several observation points (MP15, 17, 19) below the central trench (trench 9 of 17) in the model with 17 trenches during a year with average annual precipitation and assumed groundwater level GWL10m (b); groundwater level below the 17 trenches before the summer (end of May, runtime 211 d) and at the end of summer (end of August, runtime 304 d) with initial groundwater level GWL10m and average annual precipitation (c).

increased treated wastewater infiltration (end of August, runtime 304 days), it can be seen that groundwater level rises up to 2 m below the infiltration system due to the increase in the infiltration of treated wastewater.

Also, the effects of the infiltration process can be observed in the water content curves of the observation points (Fig. 3b). Due to the lateral expansion during the infiltration process, the infiltrated wastewater is distributed over the entire area below the trenches. For this reason, a zone forms in the soil (see MP 17 in Fig. 3b) in which neither the water content of the area directly below the trenches (see MP 15) nor the water content of the saturated zone (see MP 20) is reached.

Influence of groundwater levels

In order to assess the influence of the groundwater level on hydraulics in the unsaturated soil zone, two different scenarios for the model with 17 trenches were performed. In case of the GWL6m scenario, all observation points that are deeper than 6 m below ground surface (Fig. 2d, points 5, 6, 7, 12,13, 14, 19, 20, 21) are located in the groundwater from the start. The difference is also clear at observation points that are above the elevated groundwater level. As can be seen in Fig. 4a, the water content curves differ significantly at observation point 16 (2.5 m below ground surface).

Due to the chosen initial conditions for both model variants, the initial water content in the scenario GWL6m is higher than in the scenario GWL10m. In December, the two hydrographs came closer, because during this period, observation point 16 is not yet influenced by the increased groundwater level in scenario GWL6m. Observation point 16 in scenario GWL6m reaches the maximum water content in December due to intense precipitation events in combination with the infiltration of treated wastewater. At this time, the groundwater level has risen to such an extent, that MP 16 is under the groundwater level. In the scenario GWL10m, there is only a significantly smaller temporary increase in the water content, since the measuring point here is outside the area of direct influence of the groundwater level.

In February, the average water content is differing by around 0.044. This corresponds to a saturation difference of around 11%. The water content decreases again from the middle of March in scenario GWL6m and approaches the water content curve from scenario GWL10m due to lower precipitation amounts and the resulting decrease in the groundwater level.

The groundwater levels rise again in the summer period (June to August) with an increased inflow of wastewater

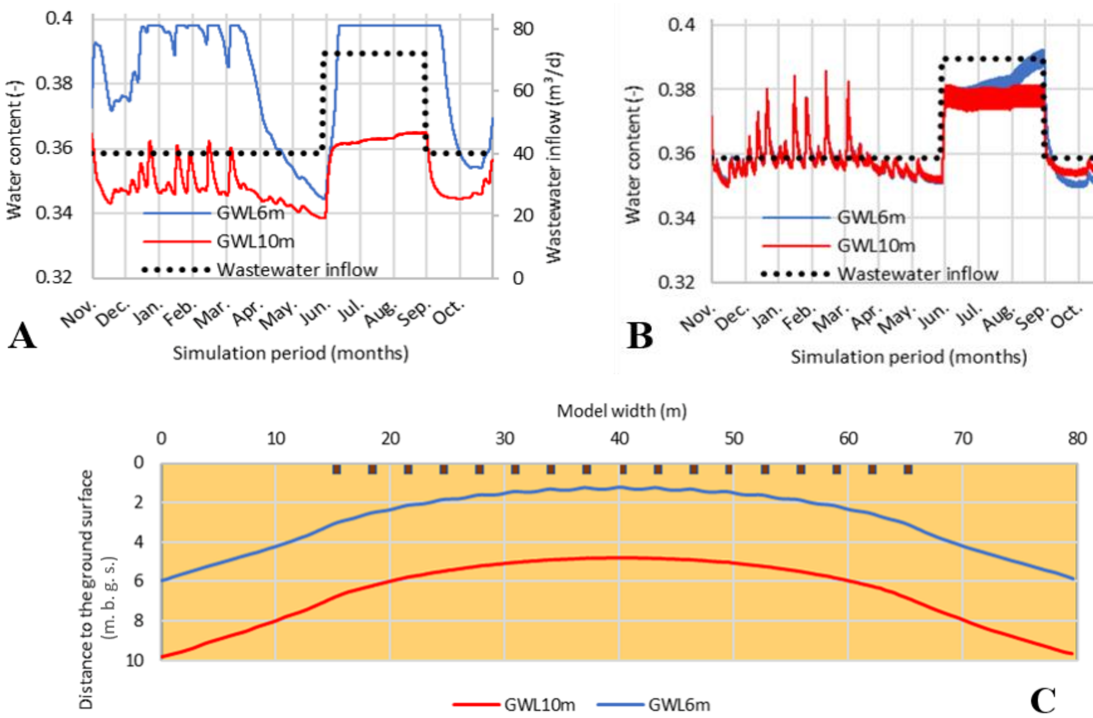

Fig. 4. Water content at observation point 16 for different initial groundwater levels for a year with average annual precipitation (a); water content at observation point 15 for different initial groundwater levels for a year with average annual precipitation 15 (b); groundwater level at the end of summer (end of August, runtime 304 d) for different initial groundwater levels and average annual precipitation (c).

caused by the higher number of inhabitants (Fig. 3c). During this period, the groundwater level in scenario GWL6m rises above observation point 16 (Fig. 4c) causing fully saturated conditions with a constant very high water content until the infiltrated amount of treated wastewater is decreasing in September. In this time, the groundwater level in scenario GWL10m in the center of the system is 4 m lower than in scenario GWL6m, so that the saturation at the observation point does not exceed a value of 92%.

The rise in groundwater during the summer up to around 1.2 m below ground surface is also influencing observation point 15 (Fig. 4b). After the water contents for both scenarios are the same from the beginning in November until June, there is an increase in the water content in scenario GWL6m due to the proximity to the groundwater level. However, fully saturated conditions are not reached.

A rise of the groundwater level up to the trenches was not observed for both scenarios (GWL10m, GWL6m) at any point in time. Nevertheless, the influence of the increased groundwater level on the saturation conditions (Fig. 4a and 4b) and the representative groundwater level (Fig. 4c) can be proven.

Influence of annual precipitation

As previously described, the average annual precipitation in the study area is around 560 mm. However, since up to 750 mm of precipitation must be planned for a year with high precipitation, the influence of the corresponding annual precipitation hydrographs on the hydraulic conditions in the unsaturated zone should be investigated. For this purpose, the water contents at observation point 15 for the model with 17 trenches were evaluated (Fig. 5a).

Despite a difference of around 190 mm per year between the amount of annual precipitation, there are only minor effects on the observed water contents at the observation points. The primary difference is caused by the different distribution of the precipitation over the year due to different precipitation events. This can be observed from the different temporary increases in water content. The water content in the summer months June, July and August is only influenced by the increased sewage inflow, because no precipitation events were recorded in the average year from May to September (Fig. 5b).

Influence of the number of trenches

After examining the influence of the factors precipitation and groundwater level on the hydraulic conditions in the unsaturated soil zone, the two potential infiltration system concepts (8/17 trenches) are compared for a year with high precipitation and an elevated groundwater level at 6 m below the ground surface. The focus here is on process reliability and thus the question of whether the treated wastewater will rise up in or even above the trenches. It can be shown that the water content for the concept with 8 trenches is constantly above the curve of the system with 17 trenches system (Fig. 6a).

The discrepancy between the mean annual water content

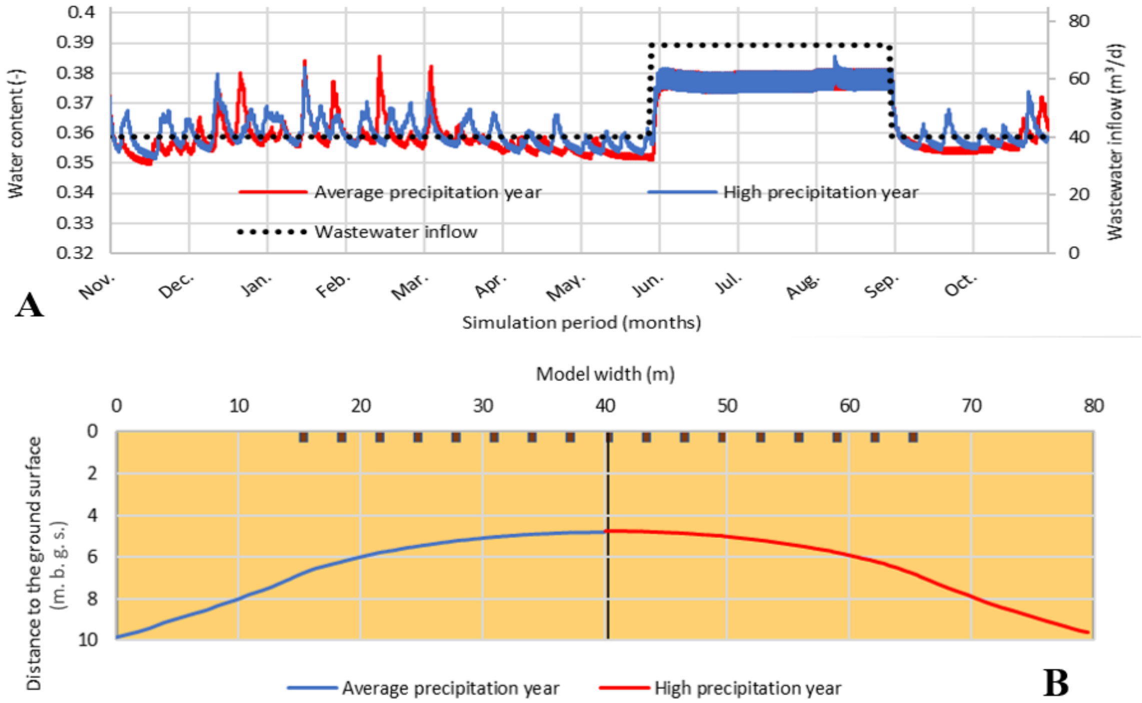

Fig. 5. Simulated water content at observation point 15 for two different annual precipitation hydrographs (a); groundwater level - left: in the average year, right: in the year with high precipitation (b).

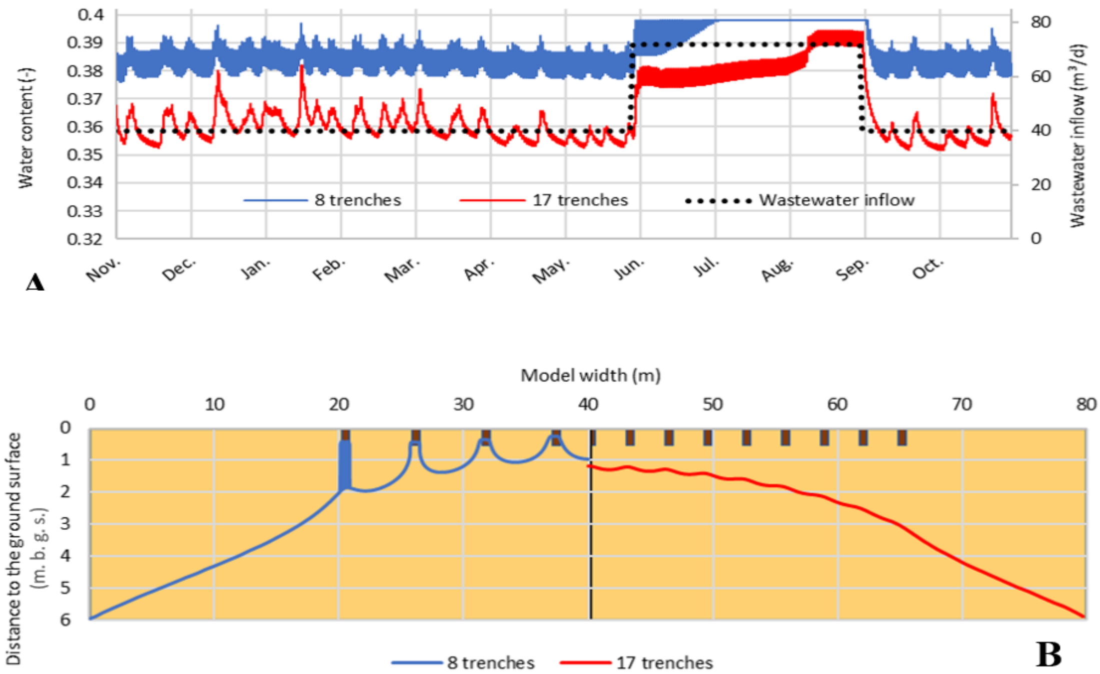

Fig. 6. Simulated water content at observation point 15 using 8 or 17 trenches for infiltration for a year with high precipitation and elevated groundwater level (a); groundwater level at the end of summer (end of August, runtime 304 d) - left: usage of 8 trenches, right: usage of 17 trenches (b).

is around 0.021, which corresponds to a mean saturation difference of around 5.3%. In addition, the maximum water content is constant at the measuring point below the 8 trenches in July and August, while the maximum water content is never reached at the measuring point below the 17 trenches.

There are two reasons for this observation. On the one hand, the inflow per trench is higher in the case of the installation of 8 trenches compared with the 17 trenches system. As a result, the flow in the soil matrix increases directly below the trenches, which is accompanied by an increase in the water content at observation point 15. On the other hand, the 8 trenches system is around 10 m smaller than the system with 17 trenches, despite the increased spacing of the trenches. As a result, the fully saturated area below the trenches increases.

During the summer months with increased treated wastewater inflow, the groundwater rises up to the level of the trenches in the system with 8 trenches (Fig. 6b). In the scenario with 17 trenches, the groundwater level rises up to around 1.2 m below ground surface at the highest point, i.e. remains around 0.7 m below the central trench.

Conclusion

After evaluating the model results, several statements could be made for a potential infiltration system in the village of Sarden:

- The study shows that in principle the infiltration of treated wastewater is possible under the climatic conditions at the Sarden site in terms of quantitative aspects.
- The increased inflow of treated wastewater during the summer months causes a significant increase in the local groundwater level and the water content below the trenches.
- The results indicate that an infiltration system with a higher number of infiltration trenches provide more process reliability and can infiltrate larger volumes of treated wastewater. Infiltration of the treated wastewater via 17 infiltration trenches does not lead to full saturation of the area below the trenches as well as the rise of groundwater level up to or in the trenches can be prevented.
- The initial groundwater level has a big influence on the saturation conditions of the unsaturated soil zone. The simulations indicate that an increased groundwater level can lead to a rise of groundwater up to and in the trenches. For planning such an infiltration system, the groundwater level plays a decisive role and has to be considered.
- The precipitation events, which were simulated and evaluated within the framework of this study, played a subordinate role for the saturation conditions within the unsaturated soil zone. Although the amount of infiltrated precipitation caused a temporary increase in the water content, it did not have any long-term negative effects on the infiltration process.

However, the simulations performed and results obtained are based on limited or assumed data on the subsurface zone and the corresponding hydraulic properties. For a better characterization of the subsurface zone, on-site investigations must be carried out to collect more data, e.g. with the help of pumping tests and drill core analyses. Further scenario analyses, which assume variation widths of the hydraulic model parameters, could also provide further validation of the findings.

Due to the mentioned limitations, the results of the study presented can only be understood as a preliminary planning step due to the complexity of real conditions at the Sarden site and their impact on the infiltration process. Furthermore, it must be noted that the results of this investigation can only be transferred to other areas to a limited extent and cannot be generalized.

Acknowledgements

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