Water is too precious to waste

Trade-offs of sewage effluent reuse in agricultural sub-surface irrigation

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Chapter 6

Synthesis: Towards comprehensive intentional reuse of sewage effluent in agricultural irrigation

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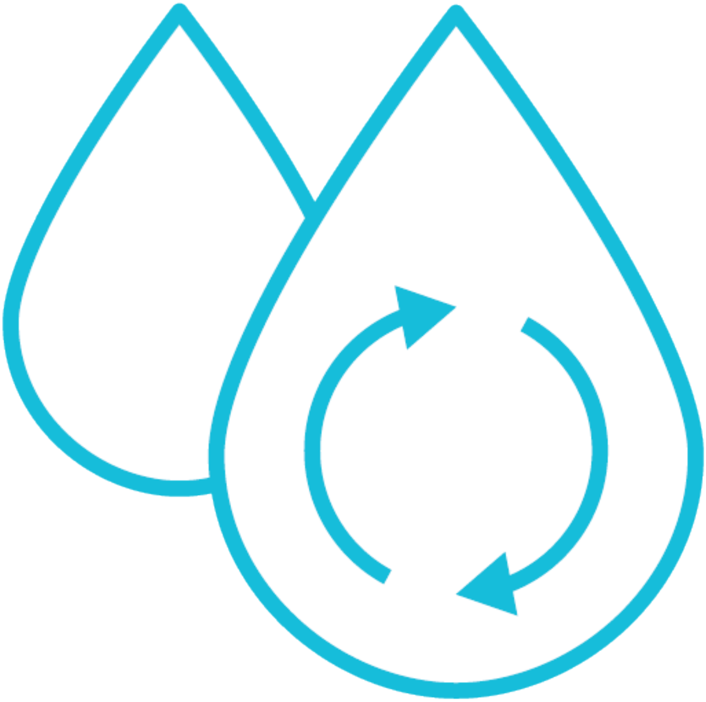

6.1 The full potential of intentional sewage effluent reuse in agricultural irrigation

The intentional reuse of sewage effluent for agricultural irrigation is increasingly considered in answer to freshwater shortages in the agricultural sector (Voulvoulis, 2018). Most reuse practices have focused on combining conventional irrigation techniques such as spray, sprinkler and drip-irrigation with sewage effluent reuse (Christou et al., 2017a). This has led to the identification of major drawbacks of sewage effluent reuse in agricultural irrigation such as the direct contact between sewage effluent and crops and the direct contact between sewage effluent and workers leading to microbial and chemical risks for consumers and workers. To combat these drawbacks, this NWO-RUST project proposes that treated wastewater (in our case sewage effluent) is supplied to a cropland through sub-surface irrigation (SSI), thereby making optimal use of the soil as an additional filter and buffer before the sewage effluent reaches the crop root zone. Besides effects on crops, also the effects of SSI on deeper groundwater and surface water need to be considered. In this dissertation, it is hypothesized that for a paradigm shift towards more intensive intentional reuse of sewage effluent via agricultural SSI, information is needed on:

I. the general risks and opportunities of sewage effluent reuse during SSI (Chapter 2),
II. the fate of CoECs in relation to their physicochemical properties during sub-surface irrigation with sewage effluent(chapter 3),
III. quantitative insights into how long-term SSI with sewage effluent leads to enhanced biodegradation and subsequently an adapted microbial community (chapter 4),
IV. the potential of SSI using sewage effluent to satisfy the agricultural water demands during periodic water shortages (chapter 5).

General risks and opportunities of sewage effluent reuse during SSI

In Chapter 2 an in depth review of the processes that affect the fate of CoECs in SSI systems, and the expectations with regards to exposure and risks are discussed. The intentional reuse of sewage treatment plant (STP) effluent in SSI, which is currently discharged in large volumes to surface water, may provide an alternative freshwater source. During drip and sprinkler irrigation, the STP effluent comes in direct contact with the crops. During SSI, the load of contaminants of emerging concern (CoECs) to surface water may be reduced due to soil passage and related (bio)transformation processes. In addition, the policies and guidelines concerning non-potable water reuse are highlighted. Worldwide, only few stated adopted guidelines related to CoECs and water reuse. At European level, the recent regulation for STP effluent reuse lacks minimum requirements for CoECs. Knowledge gaps as well as challenges and opportunities of intentional STP effluent reuse via SSI are addressed in detail in chapter 2 with the aim of stimulating future research towards an enhanced understanding of the fate and risks of CoECs in SSI.

The fate of CoECs in relation to their physicochemical roperties during SSI with sewage effluent

The work described in chapter 3 resulted in an improved understanding of how SSI systems function in combination with sewage effluent reuse. The broad selection of CoECs that were followed in an SSI system ensured that their fate could be related to their physicochemical properties, i.e. persistency and mobility. The full scale pilot and reference site allowed the observation of natural processes such as dilution and degradation during two years including the severe drought period of 2018. By normalizing the concentration of pre-selected CoECs to saccharin as effluent tracer the effect of degradation could be observed. Nevertheless, the normalization is not without uncertainties, as the residence time of the infiltrated sewage effluent is not known. The cropland is an open system, and thus can also be (in)directly influenced by other sources such as manure or regional groundwater flow. The grab sampling method in the SSI field provided snapshots on five particular moments in time. As the groundwater moves relatively slow, it could also be argued that in the case of groundwater sampling this approach is suitable.

Chapter 3 also revealed that after a severe drought period the SSI system needs more time to reset to background concentrations, whereas after a normal hydrological year with a precipitation surplus and drainage in winter, most CoECs are removed. Testing the SSI system during those events proved that the soil indeed can act as a filter and buffer zone for the STP effluent before it reaches the rootzone, deeper groundwater and surface water. So, SSI can help to significantly remove most CoECs before irrigation water reaches the crop.

However, highly persistent but less mobile CoECs do significantly buildup in the rhizosphere and shallow groundwater next to infiltration pipes. Highly persistent hydrophobic compounds can be easily removed from sewage effluent with an advanced treatment by activated carbon adsorption (Guillossou et al., 2019). Thus it is also recommended to remove this group of CoECs before they enter the cropland.

In this work a few metabolites were targeted, however a larger pool of metabolites formed remains unknown. Formed metabolites can be more persistent, polar and toxic than the parent compound (Reemtsma et al., 2016). The analysis of metabolites, which are often unknown compounds occurring in low concentrations, requires sophisticated analytical techniques such as non-target screening (NTS) based on high-resolution tandem mass spectrometry (HRMS/MS) methods combined with novel data analysis approaches (Helmus et al., 2022). It can be interesting to apply improved non-target analysis workflows including automated transformation product screening (such as patRoon 2.0) on these full scale pilot samples in a follow-up study.

Quantitative insights into how long-term SSI with sewage effluent leads to enhanced biodegradation by an adapted microbial community

In chapter 4 a six-months batch biodegradation experiment was conducted with real soils from the full scale pilot and reference field also studied in chapter 3, under aerobic and anaerobic conditions, following the OECD 307 ready biodegradability protocol. STP effluent was used to facilitate realistic concentrations, combined with the reference soil with an unexposed microbial community and the SSI soil with a pre-exposed community. The sampling method was improved by sampling the effluent at intervals for a period of 72 hours instead of 24 hours. Such environmental realistic concentrations are key in determining biodegradation rates in laboratory degradation studies, as it has been reported conducting such tests with unrealistic high concentrations influences biodegradation rates (Poursat et al., 2019). CoECs showed significantly shorter biodegradation half-lives in the pre-exposed community than in the unexposed community from the reference field. Hence, the presence of CoECs in STP effluent does stimulate mechanisms of degradation and adaptation in the soil microbiome. Recoverable shifts in microbial composition in the receiving environment were observed, in line with previous research (Price et al., 2018).

The work presented in chapter 4 emphasizes the importance of the type of inoculum used. As was seen in this work the microbial composition within one cropland is very diverse and may significantly influence the biodegradation rate. In addition, the work not only highlighted the impact continuous exposure of sewage effluent has on biodegradation rates but also emphasized the many flaws of the OECD test 307 which are commonly encountered in also other OECD tests, such as not permitting pre-exposure of the microbial community and not demanding realistic concentrations to be used during these tests.

The potential of SSI with sewage effluent to satisfy the agricultural water demands during periodic water shortages

A conscious choice that needs to be made regarding the realization of the full potential of sewage effluent reuse is the allocation of the sewage effluent. In chapter 5 the potential of intentional direct STP effluent reuse in SSI to satisfy the agricultural water demand under a temperate climate condition was assessed. For the Netherlands as case study, STP effluent can fulfil up to 25% of croplands SSI water demand present within a five-kilometer transport buffer from the STPs during an average season and 17% during a dry season. Approximately half of all Dutch croplands can be captured within the 5km buffer. Thus, it becomes evident that this type of reuse can fulfill a significant part of the water demand. Other methods to combat drought will certainly be needed. When looking at this type of reuse from a pure technical standpoint approximately 80% of effluent can be reused, meaning that 80% of effluent could be ‘filtered’ before reaching the receiving waters. This is a theoretical maximum and it should be kept in mind that minimum stream flow conditions are required for ecosystem functioning in some basins (Beard et al., 2019; Poff, 2018). Thus not all available STP effluent can be reused for irrigational purposes.

6.2 Adequate risk assessment of sewage effluent reuse in SSI

Sewage treatment plants, even the more sophisticated ones, have not been designed to get rid of lifestyle chemicals and pharmaceuticals present in influent wastewater. Consequently, several of the lifestyle chemicals that are flushed down the toilets, in particular the more polar ones, will not or incompletely be removed in the treatment plant and thus end up in the effluent and the receiving waters (Reemtsma et al., 2016). This increasing load of CoECs to surface waters is causing a rapid decline of the worlds surface water quality (Wilkinson et al., 2022). When reusing sewage effluent for agricultural SSI as appose to aboveground irrigation techniques, the soil can be optimally used to filter and buffer effluent before it reaches the crop. This may also lead to improved surface water quality, which in turn will also positively affect other sectors. However as seen in chapter 3 the persistent polar CoECs travel unfazed throughout the SSI system. Thus, a point of attention is that SSI with sewage effluent may aid in the gradual exposure of the deeper groundwater to polar persistent CoECs, which typically degrade slower under anaerobic conditions (Figure 6.1). In contrast, in aboveground techniques the rhizosphere is usually drier and there is an aerobic zone which may degrade the CoECs faster (Christou et al., 2017a). However, some aerobically recalcitrant CoECs can be bio-transformed under strictly anaerobic conditions and little is known about the organisms and enzymatic processes involved in their transformation (Ghattas et al., 2017; Reemtsma et al., 2016). In addition, obtaining consistent biodegradation rates is challenging (Greskowiak et al., 2017), as we discussed in chapter 4. Obtaining reliable removal rates of CoECs during SSI from both field and lab studies allow one to estimate CoECs loads emitted to receiving waters and modelling the resulting concentrations, so that a proper environmental exposure assessment can be made. These model results could then be combined with no effect concentrations of the CoECs, tested with different aquatic species, in order to allow a complete risk assessment to be made. Ultimately, it is important to realize that while the intentional direct reuse of sewage effluent in agricultural irrigation has potential, the selected method of supply has trade-offs in terms of water supply, STP effluent reuse and CoECs emission reduction (Figure 6.1). These trade-offs determine critical factors in upscaling SSI with sewage effluent.

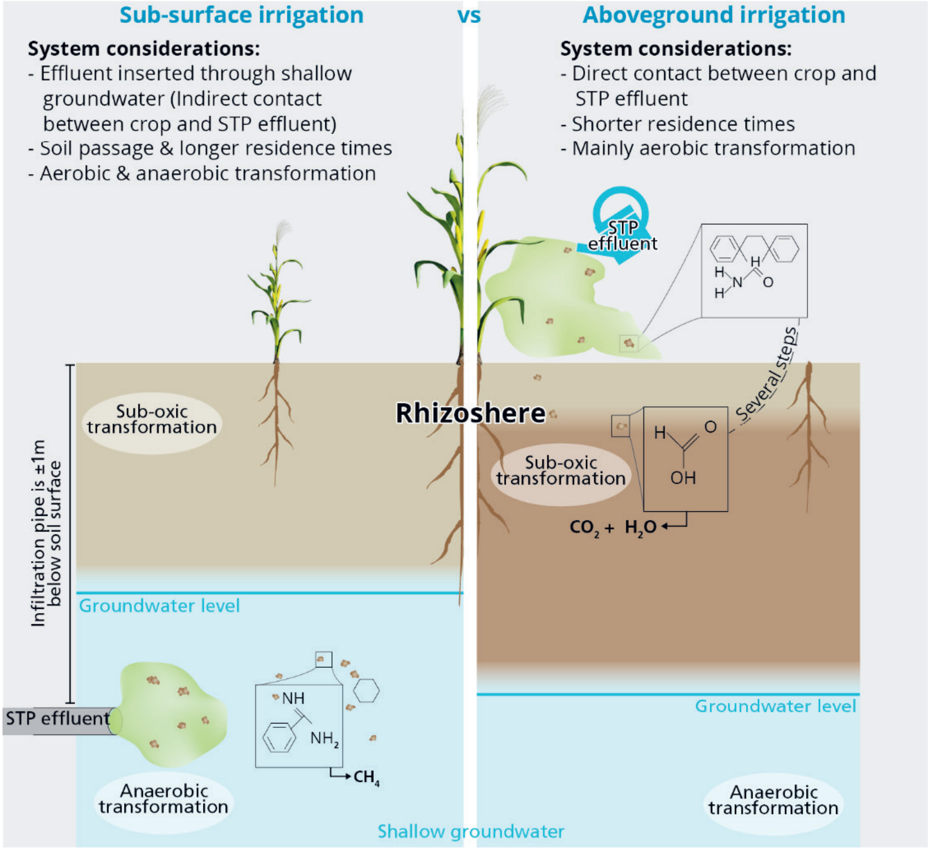

Figure 6.1 System considerations for sub-surface versus aboveground irrigation techniques.

6.3 Way forward

The previous paragraphs provide a roadmap towards comprehensive intentional reuse of STP effluent in agricultural irrigation and give insight into trade-offs that need to be considered in upscaling SSI with sewage effluent. To finalize, further research would be very interesting looking deeper into:

- the transferability of the results obtained in this work to other geohydrological and climate conditions. While this dissertation shows that the reuse of sewage effluent in SSI has potential in terms of a treatment system it is important to realize that the experimental work is based on one study area. Albeit it could be hypothesized that this study area represents a worst case scenario with sandy soil and conventionally treated sewage effluent during a severe drought period. In areas with longer and more intense drought periods the removal of CoECs may improve through biodegradation, however the groundwater level may drop down too low, making the area itself not suitable for SSI. In colder areas dilution is expected to play a bigger role as opposed to (bio)degradation.

- upgrading conventional STPs to remove persistent CoECs, especially the more polar ones as these tend to spread unnoticed through the environment as they are hard to capture, even harder to detect and there is little information known about their fate let alone their risk in the environment (Reemtsma et al., 2016). The more hydrophobic CoECs as mentioned previously could be easily removed from sewage effluent with an advanced treatment such as activated carbon adsorption (Guillossou et al., 2019).
- the reuse of more alternative freshwater sources such as industrial wastewater, apart from sewage effluent to fulfill the growing agricultural demand. The reason is obvious as water scarcity is a worldwide pressing matter, a consequence of our exponentially growing population and urbanization a better (waste)water treatment and allocation becomes crucial.
- combining efforts in retaining freshwater in the soil with reducing the amount of freshwater used and intentionally reusing all wastewater produced could further help combat drought in a wide range of sectors. Here also the use of desalinated water may come in handy considering that only a small percentage of the earth's water resources is fresh.
- creating regulations that also take into account the risk of the current situation which involves the unintentional reuse of sewage effluent through mainly aboveground irrigation techniques. As opportunities are not considered and the proposed risk analysis is very extensive, it is not possible to find a balance and implement responsible water reuse with the currently proposed regulation (Dingemans et al., 2020).

To conclude, the findings of this dissertation proof that SSI with sewage effluent can aid in transforming the linear human water cycle (abstract, treat, distribute, consume, collect, treat and dispose) into a circular flow by closing the loop, but also potentially decoupling municipal water consumption from the depletion and pollution of water reserves. However, its role in addressing water resources problems needs careful investigation and the consideration of technical, environmental and also legal aspects through a coherent analytical framework.