Water is too precious to waste

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

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Chapter 1
General Introduction

~Water is too precious to waste~

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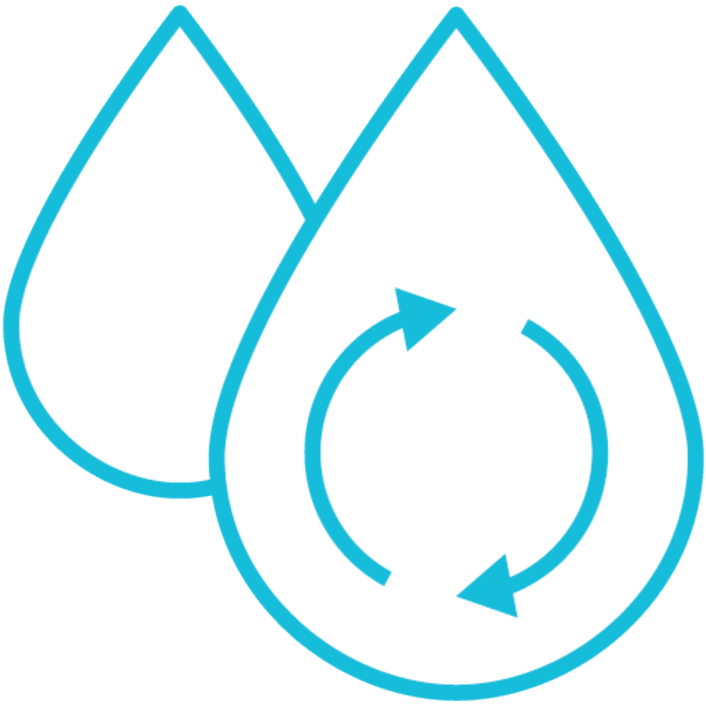

1.1 Combatting global non-potable freshwater shortages

Globally, there is an increasing mismatch between the demand for and availability of freshwater resources (UN-Water, 2018). The main causes for water scarcity of fit-for purpose water are interlinked. They include changes in water availability due to more extremes caused by climate change, increases in water withdrawal for food production and for other economic activities such as industrial cooling with water (Bijl et al., 2018). As freshwater resources in terms of both quantity and quality decline, the competition between agricultural, industrial and municipal demands will intensify (FAO, 2021). Agricultural irrigation is currently responsible for 69% of freshwater withdrawal (FAO, 2021). Water scarcity in terms of quantity and quality is not only an issue for arid regions with low rainfall and high population density that are prone to increasing water stress; also temperate areas with intense agriculture suffer from frequent non-potable freshwater shortages (Pörtner et al., 2022). The 2018–2020 and 2022 drought in north-western and central Europe emphasized the fact that even in countries with temperate climates, adaptations are needed to cope with increasing future drought frequencies (Bakke et al., 2020; "Heating up," 2022; Rakovec et al., 2022). In view of competing claims by different societal sectors, water managing authorities and the agricultural sector need to develop means to better regulate water availability for all stakeholders. Huge challenges are for instance to increase water buffering capacity for use in dry seasons, to increase surface water flow for infiltration to the groundwater and reduce the demand side from all sectors: agriculture, citizens and industry. Next to the above actions, an innovative way to increase water availability as well as water quality is to reuse effluent water. The potential role of sewage effluent reuse as an alternative source of water supply is now well acknowledged and embedded within international, European and national strategies. UN Sustainable Development Goal on Water (SDG 6) specifically targets a substantial increase in recycling and safe reuse globally by 2030. The intentional reuse of sewage effluent can compensate for water shortages caused by seasonality or by irregular availability of other water sources for agricultural irrigation throughout the year (Hristov et al., 2021; Kesari et al., 2021). Such intentional reuse offers better control and management possibilities than currently practiced (Drewes et al., 2017a) and can aid in the improvement of surface waters quality which are often affected by sewage effluent (Coppens et al., 2015; Wilkinson et al., 2022), due to current direct emissions. Especially during low flow conditions, with usually high irrigation demand, surface water can consist primarily of effluent. Water from these streams is in many cases directly applied to crops by sprinkler and aboveground drip irrigation, resulting in the unintentional direct exposure to crops of pathogens and organic micro-pollutants (Beard et al., 2019).

Neither the direct nor indirect use of sewage effluent as resource is without risks due to contaminants such as pharmaceuticals, pathogens, illicit drugs, personal care products and biocides (Kampouris et al., 2021). These are often referred to as contaminants of emerging concern (CoEC) (Alygizakis et al., 2020), reflecting that they are not routinely monitored, there are indications of their environmental presence, there is uncertainty about persistence and toxicity, and legal environmental quality standards are lacking. Active substances in pesticides are evaluated in detail before being authorized, including their environmental fate with regard to soil sorption, transformation rates, leaching to groundwater and hazardous effects to humans and the ecosystem. Other CoEC information related to mobility, persistence and hazards is part of authorization dossiers with a lower level of detail (e.g. REACH, pharmaceutical directive). Transformation products formed after use, during water treatment or in the environment are not systematically assessed. Once in the environment, the CoECs typically occur in complex mixtures which generally are concentration additive in their effects. This is a pressing problem, in view of the large number of substances used in today's society (Z. Wang et al., 2020).

1.2 Sub-surface irrigation systems as method of supply

In many temperate countries, with shallow groundwater, awareness of damage due to too wet soil conditions has been the incentive for draining much agricultural land (Brakkee et al., 2022; Zscheischler and Fischer, 2020). To prevent excessive drainage, controlled systems were developed to retain water within agricultural fields, to enable active management of groundwater level and soil wetness, and reduce surface water peak discharges and nutrient emissions (Ayars et al., 2006). Anticipatory or Climate Adaptive Drainage and

Irrigation allows to increase freshwater availability by sub-surface irrigation (SSI) of water with underground supply through drains (de Wit et al., 2022). SSI can be more efficient than classical surface irrigation methods. The main reason is that only water that is used for plant transpiration leaves the soil and groundwater system. Unused water is kept within the groundwater system (de Wit et al., 2022). SSI with treated wastewater is an emerging technology that may play a significant role in the alleviation of freshwater scarcity and water pollution. It falls under the umbrella of technologies referred to as managed aquifer recharge (MAR), which generally refer to systems that store water for a period of time while retaining or improving their quality, whilst at the same time achieving other goals such as agricultural irrigation or the reduction of coastal seawater intrusion. Thus soils suitable for SSI (de Wit et al., 2022) provide a saturated soil barrier, which when combined with sewage effluent may function as:

- irrigation water for the crops thereby tackling water scarcity in the agricultural sector;
- a filter and buffer zone for the CoECs thereby improving the water quality;
- a circular water reuse cycle that limits the use of groundwater for irrigation.

However, large-scale SSI will affect the regional allocation of water resources. Therefore, an analysis of the propagation of SSI management through the local to regional hydrological system is required to support water managers (de Wit et al., 2022).

1.3 Policies and guidelines concerning non-potable water reuse

Globally there are several guidelines, i.e. non-mandatory recommendations, available concerning water reuse. In June 2020 the regulation set by the European Commission on minimum requirements for water reuse for agricultural irrigation entered into force (The European Parliament and the Council of the European Union, 2020). The new rules will apply from 26 June 2023 and are intended to encourage and facilitate water reuse in the EU. The new regulation sets out:

- Harmonized minimum water quality requirements for the safe reuse of treated urban wastewaters in agricultural irrigation;

- Harmonized minimum monitoring requirements, notably the frequency of monitoring for each quality parameter, and validation monitoring requirements;
- Risk management provisions to assess and address potential additional health risks and possible environmental risks;
- Permitting requirements;
- Provisions on transparency, whereby key information on every water reuse project is made available to the public.

The new rules fit in the context of the 2020 Circular Economy Action Plan, which includes the implementation of the new regulation amongst Europe's priorities for the circular economy. Yet, the new regulation is still generic and provides a few minimum requirements, focused on general quality and public microbial health but lacks minimum requirements for CoECs (Partyka and Bond, 2022).

1.4 NWO-RUST project

The NWO-RUST project (File nr: ALWGK.2016.016) that resulted in the present dissertation aims to contribute to the transition to a circular economy with the focus on closed cycles. This program Closed Cycles is a cross-sectoral initiative and part of the NWO activities for the Top Sectors Agri & Food, Logistics, Horticulture & Starting Materials and Water (NWO, 2022). The program is based on public-private partnerships, as collaboration for knowledge development between companies, knowledge institutions and government bodies is required for the transition to a circular economy. The principal aim of the Closed Cycles program is to close cycles at various levels of scale within the focus areas water, agriculture and horticulture. The RUST project aims at: 1) reducing freshwater shortage in agriculture, 2) giving value to treated effluent which is now a waste product, 3) reducing emissions of CoECs into surface water and 4) developing meaningful generalizations for sorption, mobility, and persistence functionalities of CoECs. **The subsequent focus of this PhD dissertation is the fate of CoECs in sub-surface irrigation systems, in relation to their possible risks.**

A unique full field study in Haaksbergen forms the basis for the experimental work done within this PhD dissertation. This field study was setup in a 5.5ha agricultural field in the drought sensitive

Pleistocene uplands in the east of the Netherlands, next to the domestic sewage treatment plant Haaksbergen. It was (since 2015) and till this day still is the only site in the Netherlands with intentional direct effluent reuse of sewage effluent in sub-surface irrigation under real-farming conditions. A field monitoring network has been installed at this site enabling sampling of vertical profiles in the vadose zone and in the groundwater. Both groundwater levels and soil moisture conditions have been measured continuously, starting from 2015. The climate adaptive drainage and irrigation system consists of a series of subsurface drains, interconnected by a closed collector which ends in a drainage pit with an outlet. This drainage pit is equipped to remote and continuously manage the drainage basis (Bartholomeus et al., 2015; Van den Eertwegh et al., 2013; de Wit et al., 2022).

1.5 Rationale, research question and outlook

SSI with sewage effluent has the potential to be a part of the solution against the depletion of freshwater resources and it may also alleviate water pollution. It falls under the umbrella of technologies referred to as managed aquifer recharge, which generally refer to systems that store water for a period of time while retaining or improving its quality, whilst achieving other goals such as agricultural irrigation. Also in humid temperate regions managed aquifer recharge systems are needed, seasonality causes periodic (summer) water shortage in agriculture. Crop yields may decrease with insufficient freshwater availability. Where in coastal areas insufficient freshwater availability may induce salinity of soil water with additional negative effects on yields. Hence sewage effluent may provide an alternative freshwater source. When combining sewage effluent with SSI as method of supply the soil and its related sorption and biodegradation processes can be optimally used as an additional treatment and storage step before the water reaches the rootzone. Indeed, studies done in river bank filtration, managed aquifer recharge and constructed wetlands have proven that the soil may have the ability to act as a filter and buffer zone (Albergamo et al., 2019b; Hamann et al., 2016; Kahl et al., 2017). These systems are similar to SSI in terms of their anaerobic medium. It can therefore be expected that biotransformation processes which are key removal processes in these systems will also be dominant in SSI. On the other hand, these systems were constructed for purification functions, while SSI also serves as an irrigation system which leads to non-continuous infiltration and shorter residence times. This objective of SSI is the basis for the difference in design and operational conditions as compared to aboveground irrigation systems. The fate of the contaminants of emerging concern (CoECs) present in the effluent - such as pharmaceuticals, biocides, personal care products, and their transformation products - in SSI systems is not yet fully understood, in relation to the interplay between aerobic and anaerobic conditions of SSI. Furthermore, direct evidence on the adverse effects of re-using treated effluent for SSI under real farming conditions on the fate of a broad selection of CoECs is currently lacking (Revitt et al., 2021). As a consequence, to explore the full potential, i.e. risk and opportunities, of sewage effluent reuse in SSI, the main research question of this dissertation is:

How and to what degree does sub-surface irrigation with sewage effluent contribute to CoECs emission to the crop's root zone, deeper groundwater and surface water?

To guide the research, the following sub-questions are posed, which are shown schematically in Figure 1.1:

1. What are the general risks and opportunities of sewage effluent reuse in sub-surface irrigation? (Chapter 2)
2. What is the fate of CoECs in relation to their physicochemical properties during sub-surface irrigation with sewage effluent? (Chapter 3)
3. Does long-term sub-surface irrigation with sewage effluent lead to enhanced biodegradation and subsequent an adapted microbial community? (Chapter 4)
4. What is the potential of the intentional direct STP effluent reuse in SSI to satisfy the water demands in a temperate country that suffers from periodic agricultural water shortages? (Chapter 5)

To answer these questions, this dissertation integrates (i) a field scale experiment, (ii) laboratory experimentations, (iii) an ArcGis water allocation analysis and (iv) risk assessment. This dissertation firstly identifies the risk and opportunities associated with sewage effluent reuse in SSI systems based on a critical review of the literature (Chapter 2). Secondly a full-scale SSI field study was examined on the removal of CoECs based on their persistency-mobility classes (Chapter 3). Applying understanding of how SSI systems function, a controlled batch incubation experiment (Chapter 4) was set-up and operated for six months to study changes in microbial community composition and subsequent enhanced biodegradation as a result of SSI with sewage effluent. In Chapter 5 a model feasibility study was conducted in the Netherlands, a densely populated country with 1.9 million hectares cropland and well distributed sewage treatment plants across the country, as case study. Finally, the synthesis (Chapter 6) describes the main concepts and developments that need to be addressed to be able to move towards upscaling SSI with sewage effluent to larger scales. The color of the circular lines in Figure 1.1 each represent the insights that a specific chapter gives to answering the main research question. These insights all require different expertise such as chemistry, hydrology and biology.

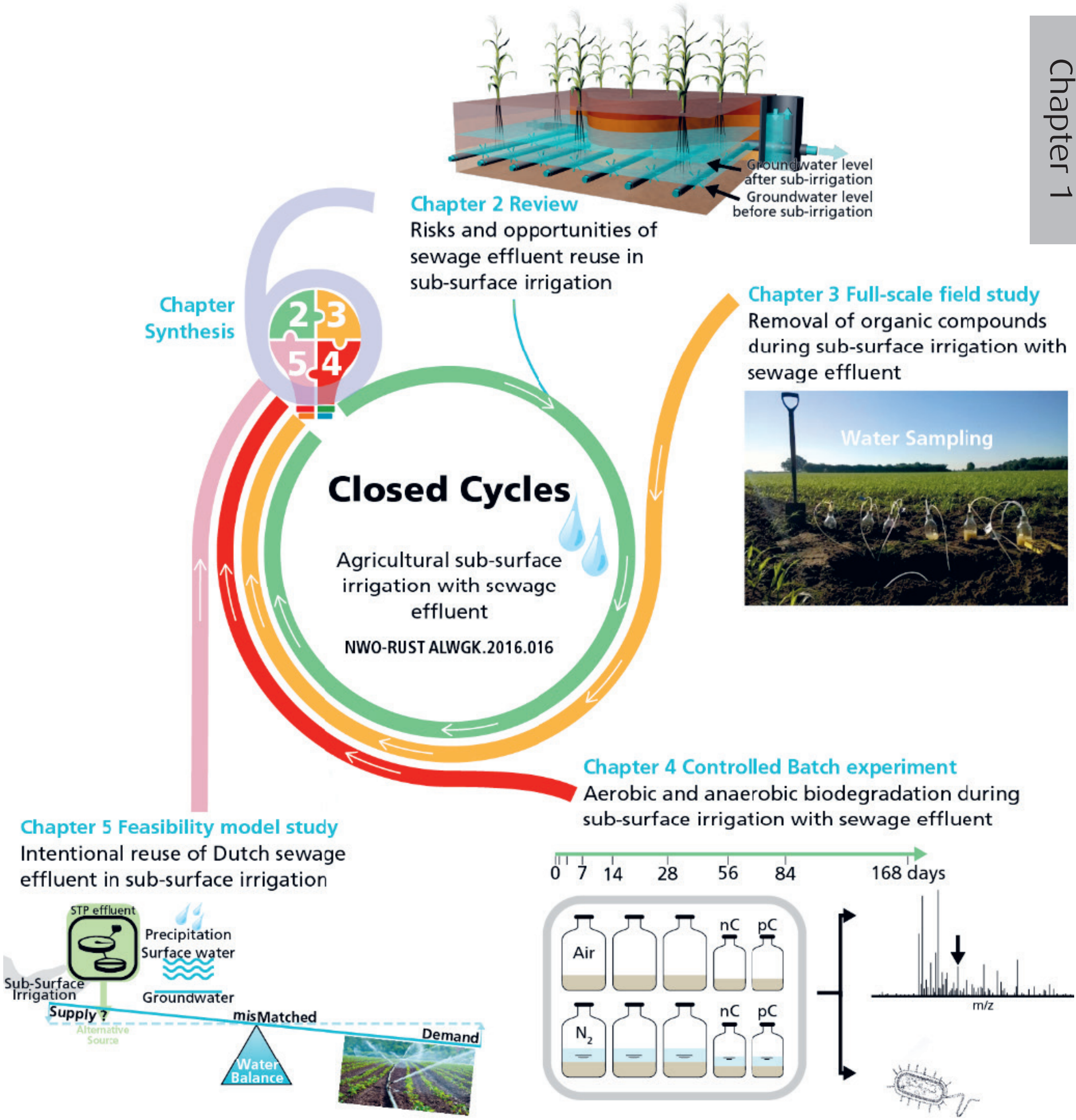

Figure 1.1 A schematic overview of the research presented in this dissertation.