MODELING OF DECENTRALIZED GREYWATER TREATMENT AND REUSE SYSTEMS IN URBAN AREAS

Sarah Manteaux[1], Mathilde Besson[1], and Mathieu Sperandio[1]

[1] TBI, Université de Toulouse, CNRS, INRAE, INSA, France

INTRODUCTION

The separation and reuse of greywater (wastewater excluding water from toilets) is one of the emerging approaches to achieving sustainable and integrated water management. This strategy reduces both the volume of potable water consumed and the amount of wastewater that needs treatment. Greywater contains few pathogens and organic matter and represents between 50 to 80% of the domestic water produced. It can potentially meet non-potable water needs, such as toilet flushing and irrigation of green areas, thereby reducing domestic water consumption by up to 50% (Maimon et al., 2010). The source separation of greywater combined with the decentralization of treatment systems, allows for the proximity of production sources and points of use. However, this approach has implications for the entire water management chain, as it requires new transport and treatment infrastructures. Additionally, centralized systems benefit from economies of scale, particularly in terms of energy consumption (Zhang et al., 2023). In the case of membrane bioreactors (MBR), a widely used technology to treat greywater due to their compactness and the stable quality of the effluent (Oteng-Peprah et al., 2018), electricity consumption increases as the scale of treatment decreases (Atanasova et al., 2017; Jeong et al., 2018; Kobayashi et al., 2020). Conversely, diseconomies of scale can be observed in the construction of sewer networks (Zhang et al., 2023), and avoiding water transport through networks is a key factor in achieving water savings (Walle et al., 2023).

Several studies have assessed the environmental impacts of greywater reclamation systems using life cycle assessment, yielding contradictory results for different scales and different energy consumptions (Besson et al., 2024; Jeong et al., 2018; Kobayashi et al., 2020; Opher and Friedler, 2016; Santana et al., 2019). There is a need to specifically study the relationship between scale and energy consumption.

The aim of this study is to identify the scale of decentralization at which the environmental impact of greywater reuse is minimized for a district. Before conducting a life cycle assessment, this study will analyze water savings, energy consumption for treatment, and piping and pumping requirements for collection and distribution networks, in order to find the optimal configuration.

MATERIAL AND METHODS

Model

The model used is the MUSES tool (Besson et al., 2024, 2021), which quantifies material flows and designs collection and treatment systems for varying flows across different types of districts. The model was adapted to generate the different fluxes of greywater (from showers, hand basins, laundry and kitchens), calculate potential reuse applications, and include a treated water distribution network.

Case study

The studied district is a hypothetical new district, with a surface of 6.25 hectares and a discontinuous buildings urban configuration (data from Bonhomme (2013)). This district comprises a mix of offices (470 employees on-across 2 office buildings) and predominantly residential buildings (29 buildings housing 922 inhabitants). The topography is considered flat.

Three decentralization scales are studied: one greywater treatment station for the whole district, one station for a block of buildings (four stations in the district) and one station per building. In the studied district, the amount of greywater available for reuse is approximately 140% of the required non-potable water (taking into account losses during treatment, see next sections and Figure 1), thus it is possible to select the building where to collect greywater and distributed to all the building. It is the mutualized scenario, where greywater from 20 buildings is collected, treated at a single decentralized station and then redistributed to all the buildings in the district.

Greywater collection and use

Greywater can be divided into light and dark greywater respectively from shower, hand basin, laundry and from kitchen wastewater. For all the different types of greywaters and uses of building (housing or office), influent characteristics (quantity and quality) are derived from a literature review. The use of kitchen greywater for reuse is often prohibited due to its lower quality (Maimon et al., 2014), so greywater from kitchen sinks and dishwashers was not collected for reuse.

The potential non-potable uses considered are toilet flushing, laundry, and irrigation of green areas. Green areas account for 18% of the district area (Bonhomme, 2013). Of these, 30% are irrigated, three times a week for six months. The total water requirement for irrigation was distributed among the buildings by dividing the district requirement by the number of buildings

Figure 1 shows the balance of greywater production (in dark and light grey) and the potential uses for non-potable water (in green and dark grey) in residential and office building. A complementarity between the two types of building is shown: the needs are higher than the resource in office building whereas it is the inverse in residential buildings due to excessive amount of shower greywater. Globally in the mixt district non-potable water needs are covered by 55% of greywater production. In the model, it was assumed that only greywater produced during the day can be used to meet that day's non-potable water needs, in order to avoid too long storage.

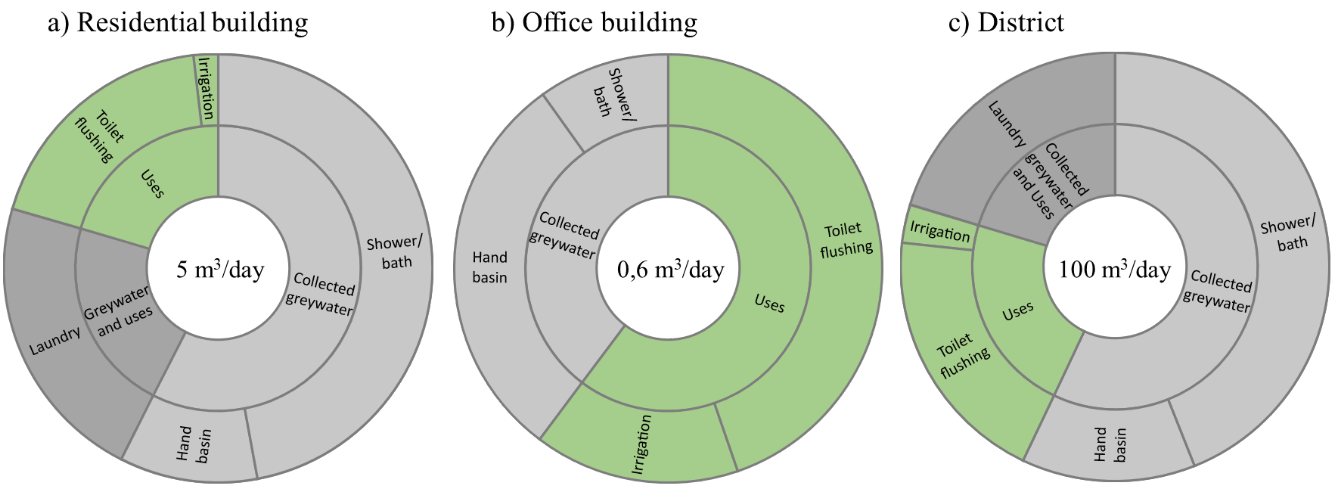

Figure 1: Average daily greywater production (in DARK and LIGHT GREY) and potential uses (in GREEN and DARK GREY) for a) a residential building of 50 inhabitants, b) an office building with 50 employees and c) the studied district (922 inhabitants and 470 employees)

Networks and treatment

In the scenario blackwater and kitchen greywater are collected via a gravity sewer and transported to a centralized treatment plant located outside of the district. Light greywater (from showers, hand basins and laundry) is collected through a gravity sewer and transported to a decentralized treatment station. If the depth of the sewer exceeds 4 meters, a pumping station is installed and designed accordingly.

Only the amount necessary to meet the non-potable water needs is treated, with any surplus being sent to the blackwater gravity sewer. It was assumed that 20% of water was lost during treatment. Variations in the energy consumption of MBR related to the quantity treated are referenced from (Kobayashi et al., 2020) which extrapolates from the energy requirements of different scales of MBRs. Treated greywater is distributed to each building with a pressurized network. An energy consumption of 0.4 kWh/m^3 was taken (Santana et al., 2019).

RESULTS

Water savings

All non-potable uses are met with collected greywater at both the block of buildings and district scales (Figure 2). At the building scale, 97% of the uses are met, with the missing flow occurring for buildings with less than ten inhabitants on irrigation days and for office buildings. With the mutualization, there is a 6% shortfall in greywater supply, but the surplus (excess water collected and conveyed to the decentralized station) is reduced from 41% to 3%.

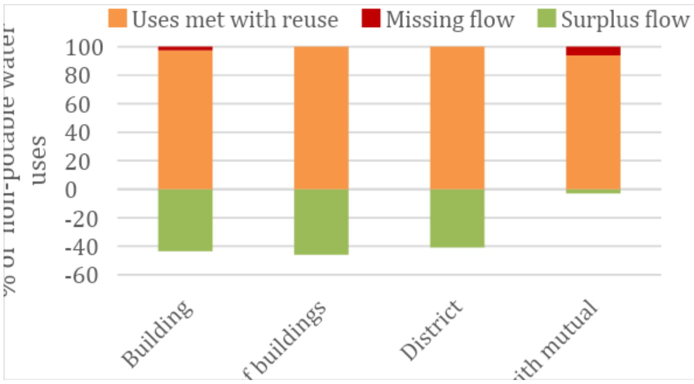

Figure 2 : Annual percentage of non-potable water requirements met with greywater reuse, greywater collected for reuse in surplus and missing flow at the decentralized station to meet the requirements

Energy consumption

Treatment accounts for over 70% of the total energy consumption (Figure 3-a.). It is 1.8 times higher at the building scale and 1.3 at the block of buildings scale compared to the district scale. Mutualization slightly reduces energy consumption for treatment due to a lower volume of water being treated (Figure 3-b.). The impact of the gravity sewer energy consumption is low with respect to the total energy consumption (0-2%). The energy required to pressurize the distribution network represent 17 to 27% of the total energy consumption.

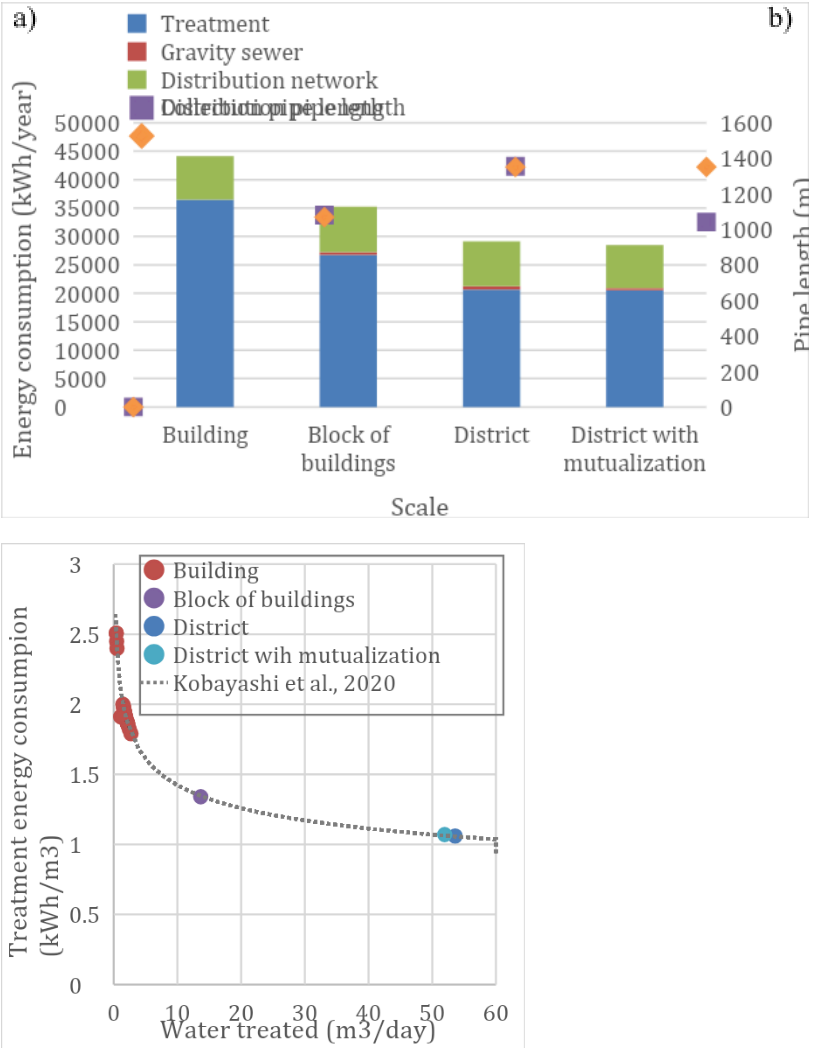

Figure 3 : a) Total greywater reuse system energy consumption and b) Treatment energy consumption according to the treated flux

Network pipe length

With four treatment stations in the district (block of buildings scale), the lengths of both the greywater gravity sewer and the treated water distribution network are reduced by 20% compared to the district scale (Figure 3-a). Collecting greywater from only 20 out of 31 buildings decreases the length of the gravity sewer by 23%.

DISCUSSION

Greywater reuse meets all or nearly all non-potable water needs. The minor shortfall is attributed to variations in greywater production and use throughout the year and specific site characteristics (e.g., office or residential settings, number of inhabitants). Except in the mutualization scenario, 40% of the greywater collected is in surplus. Additional non-potable uses could be considered, such as cleaning, fire extinguishing, or boiler feed water (De Gisi et al., 2016). Alternatively, laundry could be excluded from reuse sources.

Treatment is the largest contributor to energy consumption and nearly double with the smallest decentralization scale. However, the effect of the scale of this type of treatment on energy consumption is not well understood. Jeong et al. (2018) used values ranging from 1.1 to 0.45 kWh/m^3 for flow rates of 0.3 to 1.8 m^3/d respectively, based on manufactured MBRs, while this study found an average of 1.9 kWh/m^3 at the building scale with a flow rate of 1.7 m^3/d. Optimizing parameters according to different scales could reduce this energy consumption.

The energy consumption of the distribution network was estimated based on a value from the literature. However, this value varies widely, ranging from 0.14 to 1 kWh/m^3 (Jeong et al., 2018; Knutsson and Knutsson, 2021).

Furthermore, a single energy consumption value per unit of transported water was applied across all scenarios, without accounting for variations in network length or building height. To improve the accuracy of energy requirement estimations, head losses along the distribution network and within buildings will be calculated for all scenarios.

CONCLUSION

Key factors influencing the environmental impact of greywater reuse were studied: the amount of water treated relative to demand, the energy consumption associated with the treatment and the additional network required, for building to district scales. The results of this modeling will be used in a life cycle assessment and compared to a centralized scenario. This will help identify the most sustainable scenarios for greywater decentralization, and provide guidance for designing of new wastewater management systems.

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