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Exploring transitions of sewer wastewater infrastructure towards decentralisation using the modular model *TURN-Sewers*

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ABSTRACT

We present a new modular model called *TURN-Sewers* for exploring different adaptations of centralised wastewater infrastructure towards more decentralised wastewater systems under different urban development scenarios. The modular model is flexible and computationally efficient in exploring transitions at the city scale, allowing for the comparison of different policies and management strategies for sanitary wastewater infrastructure. *TURN-Sewers* includes independent modules that simulate the generation, dimensioning, deterioration, management, and calculation of performance indicators for different wastewater systems. This model can use readily available spatial information to support infrastructure planners and other stakeholders in exploring different transition pathways from centralised to decentralised wastewater infrastructure. An illustrative example demonstrates how *TURN-Sewers* can generate multiple future alternatives, define different infrastructure management strategies regarding system expansion, rehabilitation and transition, and assess the economic, hydraulic and structural impacts.

1. Introduction

1.1. Why contemplate urban wastewater system transition?

When it comes to urban drainage infrastructure, 67 % to 99 % of the population in OECD countries are connected to a centralised sanitary sewer system (OECD 2023). However, due to ageing infrastructure and climatic, demographic, technological, urban, and socio-economic developments, current infrastructure needs to adapt to cope with the future capacity, resilience and sustainability demands.

While traditional centralised sewer systems have been the norm for urban drainage infrastructure, research shows that there might be better ways forward. (Maurer et al., 2005; Marlow et al. 2010; Baron et al. 2016; Larsen et al. 2016; Hoffmann et al. 2020). Instead, increasing interest is in deploying decentralised wastewater treatment solutions as a more sustainable alternative. These solutions, which include on-site or distributed sanitation systems, can potentially reduce water stress and promote more circularity (Larsen et al. 2013). They also offer benefits such as increased flexibility and resilience to extreme events, particularly when managing sanitary wastewater and stormwater separately (Bach et al. 2018; Hesarkazzazi et al. 2022a). The implementation of these type of systems has not yet being widely implemented due to path dependencies (Maurer 2022) such us the lock-in effect from sunk costs of existing infrastructure, lack of guidance and some institutional obstacles (Gandenberger and Sartorius).

Resource-efficient drainage solutions include more recent concepts for stormwater management, increased water productivity, decentralised or on-site wastewater treatment, source separation of human waste, and institutional and organisational reforms (Guest et al. 2009; Larsen et al. 2016; Hoffmann et al. 2020). Separate management of sanitary wastewater and stormwater through decentralised technologies enables more efficient system layouts with higher flexibility and increased resilience to extreme events (Sharma et al. 2010; Eggimann et al. 2016a; Larsen et al. 2016; Eggimann et al. 2017). Whereas many recent studies have investigated the spatial and functional integration of decentralised storm water solutions (Wong and Brown 2009; Sharma et al. 2010; Poustie et al. 2015; Baron et al. 2017; Bach et al. 2020), the integration of decentralised (on-site or distributed) sanitation systems and their impacts on the sanitary wastewater management systems are less frequently studied (Maurer 2022).

Decentralised sanitary wastewater management is promising to address water and resource scarcity challenges, as they can locally treat

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and reuse wastewater flows rich in nutrients and organic substances at small scales (Larsen et al. 2013). These include combinations of treatment technologies such as sequencing batch reactors, membrane bioreactors, biofilm reactors, activated sludge reactors, among others, can be applied (Guest et al. 2009; Makropoulos and Butler 2010; Tilley et al. 2014; Larsen et al. 2016).

Their embedding into – and combined – within an existing centralised sewer system is paramount for developing long-term planning tools that allow stakeholders to quantitatively explore the consequence of including decentralised elements and transition towards different future system configurations.

1.2. Supporting the exploration of wastewater system transition pathways

Adapting existing infrastructure by expanding or integrating decentralised treatment technologies is a complex undertaking. Unlike complicated problems that can be broken down into simpler components, complex problems are difficult to comprehend and predict due to the interactions and interdependencies between elements (Nason 2017). Urban water infrastructures present a high level of complexity and interconnection between components used, with a very pronounced spatial and temporal dimension, making it challenging to comprehensively evaluate their planning, rehabilitation, management, and modelling (Hesarkazzazi et al. 2022a). Due to the high degree of possible combination of technical elements, the adaptation process needs to evaluate and compare multiple alternatives for the chronological and spatial integration of innovative decentralised treatment technologies into the existing sanitary systems.

Generating alternatives into which a system can be transformed involves creating possible combinations of technological solutions while considering the physical constraints of a system in addition to stakeholder preferences. To tackle these challenges, Davis et al. (2007) suggest the need for models that analyse numerous sewer infrastructure alternatives and future scenarios while maintaining information about the urban characteristics and associated water infrastructure. However, this can result in thousands of alternatives that must be analysed and screened (Zischg et al. 2019). Previous studies have utilised multi-objective optimisation techniques like genetic algorithms to speed up this process and find optimal solutions based on cost and water management objectives. However, such approaches can result in overly restricted use of options that may eliminate potentially more practically viable alternatives (Keeney 2002; Maringanti et al. 2009; Spuhler et al. 2018).

1.3. Available modelling tools and development needs

Hesarkazzazi et al. (2022b) and Zhang et al. (2023) use a graph-theory-based combinatorial multi-objective optimisation approach to create decentralised layouts for urban drainage systems. Hesarkazzazi et al. (2022b) note that choosing a suitable sewer structure (topological layout) to disconnect from the centralised sewer network early in the planning process can significantly impact both the final network's resilience and the construction costs of the conduits. Their study does neither consider the need for decentralised wastewater treatment services in disconnected areas nor the operational costs of networks and wastewater treatment. These issues are tackled by Zhang et al. (2023) in the SUWStor model, where the authors implemented a multi-objective optimisation model to find optimal solutions for the layout of decentralised urban wastewater infrastructure given potential locations for decentralised WWTPs. The model uses the ant colony optimisation algorithm to minimise capital costs, minimise operational energy consumption, and maximise water reuse capacity in the system and presents the pareto-optimal solutions. Even though, the model gives solutions for one particular point in time, each simulation is computationally takes about 17 h, which makes it unsuitable for transition planning over time. Both models neglect transitions of the urban drainage infrastructure, where growth in urban areas or other changes in urban characteristics influences a network's design through time.

This shortcoming has been recognised by different authors who have presented integrated models to study transitions in urban drainage systems. For example, the DAnCE4Water model can simulate transitions in urban water systems over a long period, which can provide valuable insights for future planning decisions (Urich et al. 2013; Rauch et al. 2017). It can replicate the societal, urban and biophysical dynamics with spatially explicit details under a range of future conditions and development trajectories. However, as the model replicates the infrastructure and dynamics in a specific urban catchment, it requires a lot of detailed data. The individual sub-model simulations are run individually and integrated iteratively to replicate the dynamics of the urban water system, which requires significant computational resources and expertise to use the model.

Another example is the SinOptikom model, which is also highly detailed and optimises the transition of combined sewer networks to source-separated wastewater systems with decentralised treatment over a 50-year period (Baron et al. 2015; Baron et al. 2017). The SinOptikom approach was applied to small rural villages in Germany and their specific local infrastructure layouts. Underlying details regarding data and the model are not made publicly accessible.

From a long-term planning perspective, DAnCE4Water and SinOptikom require significant amounts of data and computational resources that make them unsuitable for broad exploratory modelling at a city level, where detail fidelity to the individual pipe level is not needed nor useful.

Therefore, creating sewer network models with different levels of spatial abstraction is necessary to tailor the model to the task at hand and compare multiple alternatives while retaining the integrity of the urban characteristics and associated water infrastructure information. The UrbanBEATS Planning-Support Model (Bach et al. 2020) was explicitly created to plan stormwater management solutions in urban catchments. It considers various high-level data sets, including land use, population, and elevation, spatially disaggregated into a gridded map of cells called blocks. The size of each *block* is flexible and can vary depending on the modelling objectives. Along with the earlier observations regarding emphasis on modelling decentralised stormwater solutions rather than decentralised management of sanitary wastewater, UrbanBEATS does not include sanitary wastewater collection nor treatment infrastructure, nor does it consider the transition over time.

In order to adequately address the challenge of replacing or adapting infrastructure elements, it is important also to consider the costs of sunk infrastructure and the potential benefits of alternative solutions (Maurer 2022). This requires a careful assessment of the existing infrastructure's specific characteristics, including using deterioration models. Failing infrastructure opens windows of opportunities where decisions must be made to replace or adapt infrastructure elements.

In addition, with cost considerations being a relevant evaluation criterion in decision-making, spatially-dependent economies of density have a high impact on the usual cost-driving factors that are not considered in the models mentioned above – think of context uncertainties, economies of scope, economies of scale, or high network infrastructure lifespans (Hansman et al. 2006; Markard 2009). The total life-cycle cost of wastewater infrastructure systems depends on the sum of the capital and operational costs of the individual technological components and how those components are distributed spatially (Eggimann et al. 2016b).

Eggimann et al. (2016a) propose a framework for a total cost assessment of sanitation infrastructures in each region for the full range of degrees of centralisation. The total costs comprise the treatment and transportation costs of centralised and decentralised wastewater management systems relative to specific Connection Rates (CR). The authors use this framework to optimise the CR so that wastewater services are provided at the lowest overall regional cost or that households can choose to connect or not. These two optimisation conditions resulted in different CR and highlighted the importance of considering the management strategy as a critical component for modelling system transitions.

1.4. Contribution of the herein presented TURN-Sewers model

This paper presents a modular model for ‘Transitions in URban Networks towards decentralisation in Sewer systems’ (*TURN-Sewers*). The purpose is high-level urban infrastructure planning to explore potential transformation strategies of sanitary urban drainage systems for specific locations in the city and evaluate their performance over time. We do not aim at detailed engineering design. The model can generate transition pathways for decentralising sanitary sewer systems (hereafter: sewer systems) at the city scale to possible future states. In this paper, we focus on the comparison between centralised versus decentralised connectivity of new urban areas in expanding cities.

TURN-Sewers uses a spatially simplified representation of the urban characteristics and generates the urban drainage infrastructure using the same approach as Duque et al. (2022). This conceptual modelling approach helps manage computational complexity while retaining the detail to approximate infrastructure layout, function, and performance outcomes.

To create transition pathways to possible future system states, we consider:

(i) expanding and (ii) re-dimensioning the sewer infrastructure when and where needed, (iii) using infrastructure failure as an opportunity to replace it, (iv) implementing various infrastructure management strategies, and (v) quantifying system performance using indicators that reflect economic, hydraulic, and structural characteristics.

The paper is structured as follows: The principles and structure of the model are described in chapter 2, providing an understanding of how the model works. Chapter 3 focuses on the input requirements and a basic implementation of the modules. Chapter 4 presents an illustrative example case as a demonstration of model. We explore the conditions that might favour the implementation of decentralised wastewater treatment in urban areas. The limitations of the model and outlook are discussed inchapter 5, providing clarity on the model’s current capabilities and potential for future development. Finally, the paper concludes with a summary of the model’s benefits and the potential for future research.

2. *TURN-Sewers* in a nutshell

2.1. General approach and modular structure

TURN-Sewers can generate multiple transition pathways for existing sewer systems. It accommodates the growth of the catchment and considers the deterioration of existing infrastructures. Different management strategies allow for maintaining and expanding the existing network or replacing it with more decentralised solutions. The strength of the modular model is that it does not track every single pipe but creates a standardised pipe network that allows for changes in the urban fabric.

The transition pathways are generated based on existing infrastructure and the projected urban development in the catchment area. Both pathways start at the same point in time and with the same urban characteristics. We generate a virtual network that is the simplified representation of the centralised sewer infrastructure using the algorithm proposed by Duque et al. (2022). This simplified representation allows us to quickly generate multiple feasible (not necessarily optimal) solutions over time within a short computational time. For the following time steps, depending on the management strategy regarding the connectivity, the expansion areas can be connected in a centralised way or we assign decentralised wastewater treatment plants (WWTP) to each new expansion area. In each time step the infrastructure of the previous time step is considered and no infrastructure is deconstructed.

The simplified sanitary sewer system generator, as presented in Duque et al. (2022) disaggregates the spatial and population characteristics of the urban area over a squared grid of *‘blocks’* following the same principle of the UrbanBEATS model for stormwater infrastructure placement while generating an abstract spatial representation of the sewer system. The wastewater of all blocks is managed – either by collection and drainage to a sewer leading to a centralised wastewater treatment plant further downstream or by decentralised in-block treatment. The detailed connecting infrastructure inside the block is neglected, and the abstraction layer’s resolution can be chosen as required. A smaller grid size increases precision and vice versa.

Adaptations to transform the system towards decentralised wastewater systems may include disconnecting city areas, replacing old sewer infrastructure with new decentralised approaches, or using decentralised treatment technologies in new urban areas. The combination of multiple adaptation measures implemented over time results in an alternative layout of the sewer infrastructure, as illustrated in Fig. 1. Subsequently, the change from one layout alternative to another one in the future is referred to as a ’transition’. The path from the initial state to the resulting state at the end of the time horizon is the ’transition pathway’. This approach allows us to explore and compare potential system transformations in urban areas.

The main modules of *TURN-Sewers* and their inputs and outputs, from the spatial delineation of sewer systems to their performance evaluation, are illustrated in Fig. 2 and described in more detail in chapter 3.

We want to emphasise that there are several possible implementations of the modules, depending on the purpose for which *TURN-Sewers* shall be used. *TURN-Sewers* is modular and can be coupled with other implementations, allowing model developers to tailor it to the specific needs.

2.2. Modularity, model implementation and access

TURN-Sewers is designed as a modular model consisting of five modules presented in Fig. 2. The output of one model serves as the input of the next one. This feature also allows for potential future parallelisation across the different modules. The details in each module can vary to simplify or enhance the complexity of the system that is being modelled. For example, the complexity of the deterioration model can be adapted in the ‘infrastructure deterioration module’ or the management strategies can be formulated in the module ‘management strategies’ to explore different transition pathways.

The model was implemented in Python 3.9 and is available in the following repository https://gitlab.switch.ch/sww/turn-sewers

3. *TURN-Sewers* input and modules

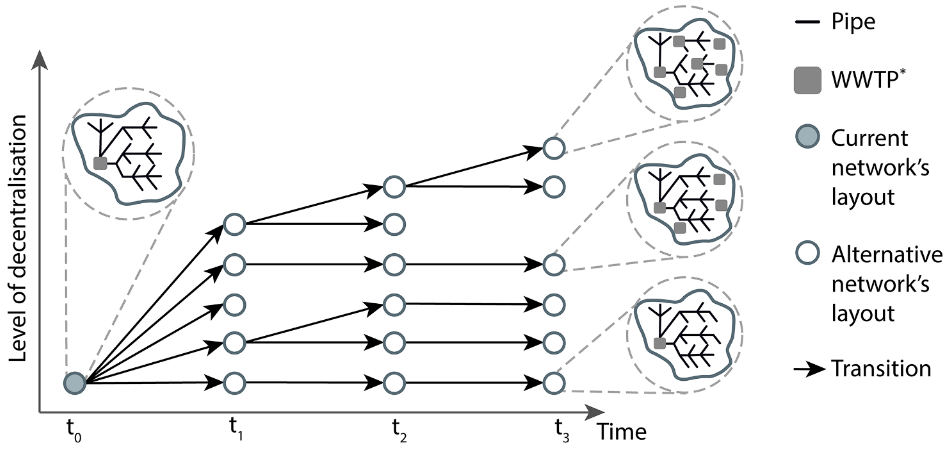
3.1. Input data and urban dynamics

3.1.1. Catchment definition

The model requires basic information about the topography, land use classification, and population density of a specific urban catchment area disaggregated into a square raster or *‘blocks’,* as Duque et al. (2022) described. The spatial relations between the blocks are known, and the minimum block size is 200 m by 200 m. In addition, the average daily water consumption per capita is used to compute the expected wastewater production, considering the specific demands of different land use types.

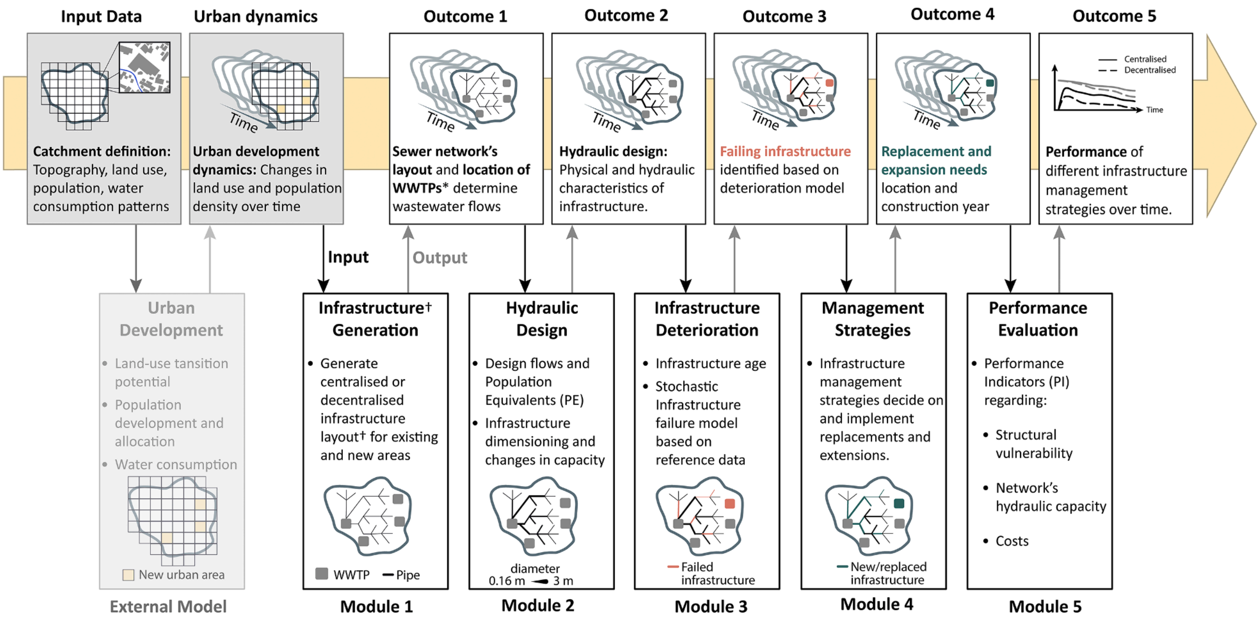
3.1.2. Urban development dynamics

For each timestep, we need a description of changes in land use for each *block* based on its ‘transition potential’ towards different land use. These data can be taken from an urban development plan or generated from a model that describes the possible spatial changes in land use and population density within a city over time. The model used by us is



* WWTP: wastewater treatment plant

Fig. 1. Scheme of potential transition pathways for generating wastewater infrastructure with different levels of decentralisation.



* WWTP: wastewater treatment plant
† Infrastructure: refers to wastewater pipes and WWTPs.

Fig. 2. TURN-Sewers modules and modelling sequence. Boxes on the top present the outputs per module that serve as input for the following modules. Boxes at the bottom present the modelling modules and their fundamental functions. White boxes refer to original contributions of the TURN-Sewers model, and grey boxes are input data or external models upon which TURN-Sewers is built (see main text for details and references).

implemented in 'UrbanBEATS' (Bach et al. 2020) and relies on the MOLAND Model's urban and regional land use dynamics elements (White et al. 2015). The result reproduces detailed land-use developments within the city following local planning rules. This model is not a part of TURN-Sewers; see the appendix for details (chapter A.1).

The output consists of multiple maps, one per time step, reflecting changing population counts, distribution and land use classification, i.e. the *Urban development dynamics*. For example, an area with a green park could have changed to a residential area from one-time step to another, and the population in that area of the city would also have increased. The relevant information for the wastewater infrastructure generation module is the population, average elevation, proportions of land use within the block, the corresponding water consumption, and the spatial relations among the blocks.

3.2. *Infrastructure generation module (Module 1)*

A fundamental assumption underlying the model is that all wastewater is managed by conveyance or localised treatment. Therefore, this module identifies for every block, whether wastewater is produced and generates the infrastructure needed to deal with it. All infrastructure needed within the block is lumped together. We assume the 'existing' infrastructure in year 0 is a fully centralised system. We implemented the following infrastructure expansion approaches for the sewer topology delineation and treatment allocation across blocks:

- Centralised alternative: New pipes are added to the network's inventory in areas with residential, commercial and/or industrial land use. The expansion of the network considers the flow direction and new capacity requirements for new and existing infrastructure.

- Decentralised alternative: This area is disconnected from or, for new blocks, not connected to the existing centralised network. New small-scale treatment plants equip new development areas (one small-scale WWTP per block) and presume a regular local conveyance system within the block.

The hydraulic dimensioning follows in module 2, and the decisions for building or exchanging infrastructure are implemented in module 4.

For the centralised alternative, we use an extended version of the approach proposed by Duque et al. (2022) to generate the development of the sewer system over time. The layout and dimensioning of the foul sewer infrastructure are based on the urban characteristics of the city (i.e. land use mix, population density, and existing infrastructure). Sanitary (foul) sewer infrastructure is 'placed' in blocks with a non-zero population density or commercial industry use. Based on the wastewater production per block, the sewer network is dimensioned using the Pipe-by-Pipe algorithm, routing the wastewater towards a centralised treatment point. This design algorithm gives a feasible sewer topology with a low computational effort (Duque et al. 2022).

Alternatively, in a decentralised alternative the existing centralised network is rehabilitated, while – depending on the management strategy – newly developed areas are left disconnected and receive a new small-scale wastewater treatment for the expected load or the block measured in population equivalents (PE). In this case, centralised and decentralised wastewater technologies coexist in the same system, ensuring complete wastewater management. The dimensioning of the treatment is done in module 2.

The outcome of module 1 is the sewer network layout and the locations of all the treatment plants in the catchment area.

3.3. Hydraulic design module (Module 2)

In this module, the infrastructure capacity (from module 1) is determined. We assume that the quality of the treatment plant performance is independent of size. Treatment plants are designed based on the estimated or forecasted capacity in population equivalents (PE). We estimated residential loads as $PE_{res} = Inhabitants_{block}$. For industrial loads, the conversion is not straightforward since the PE depends on the type of industry. We use Eq. (1) to calculate the non-residential (commercial and industrial) load PE_{non_res}, where $WW_{commercial\_block}$ and $WW_{industrial\_block}$ are the wastewater discharge from commercial and industrial sources, respectively. Q_{daily_avg} is the average daily water consumption per capita:

$$PE_{non\_res} = \frac{WW_{commercial\_block} + WW_{industrial\_block}}{Q_{daily\_avg}} * f_{non\_res} \tag{1}$$

f_{non_res} is a scaling factor to reflect peak flow for non-residential areas and needs to be estimated or derived for a specific setting. For our current implementation, we use a value of 2.8 for all blocks, a typical peak factor for non-residential areas in Switzerland. This peak factor would need to be identified for any specific case study.

The capacity of a newly built wastewater treatment plant is based on a forecasted or estimated capacity at the end-of-life of the plant. This can be the actual growth rate taken from the urban development dynamics or based on an estimated growth rate. The idea is to mimic design reality, where the effective growth rate is unknown at the time of building the plant. For the illustrative example, we assumed that design guidelines for wastewater treatment plants request an exponential growth rate of 1 % per year, during the lifespan of each WWTP.

The design of the sewer network, with its corresponding hydraulic constraints, is the same as presented in our previous work (Duque et al. 2022). A summary is presented in the appendix (chapter A.2). We use a set of available commercial diameters ranging from 0.11 m to 3 m. The hydraulic design model also defines the depth at which the pipes are installed. When pipes exceed the maximum excavation limit (5 m), the pipe is raised to the minimum excavation limit employing a pump. On the contrary, when the minimum excavation depth is not reached at the downstream extreme of the pipe, the pipe is lowered to meet the excavation limits through a drop. This process is also detailed in the appendix (chapter A.2). Please be aware that the current implementation does not track the pumps as a separate asset but is considered part of the sewer network.

The outcome of Module 2 is the complete theoretical hydraulic design of the sewer system and wastewater treatment plants. This module does not impact the modelled infrastructure but serves as an input for module 4, where the decisions are made.

3.4. Infrastructure deterioration module (Module 3)

The deterioration module aims to model the end-of-life of pipes and treatment plants. Repairs or renovations are not implemented. Therefore, the current implementation does not model condition or deterioration states (nor corresponding asset management strategies). Each type of infrastructure asset can have an independent failure behaviour.

In the case of the WWTPs, we assume a fixed lifespan, after which they must be replaced. In our current implementation, we parameterised the lifespan of centralised WWTP (PE>5000) to fall between 20 and 25 years, while small-scale or decentralised treatment facilities (PE<5000) have a 20-year lifespan.

The replacement times of sewers often do not reflect only the time when an asset has lost its function but rather the time when it was considered necessary to replace the asset due to a combination of factors, such as the potential risk and hazard or an opportunity due to coordinated replacement of sewers with other adjacent infrastructure or regular maintenance. We have chosen to quantify sewer deterioration and hence the probability of failure using a parameterised survival model. The applied failure model assumes that a Weibull distribution can approximate the time to the end-of-life according to Eq. (2), where the probability density function (PDF) describes the probability of failure of a pipe given the age θ and with β_1 as the scale and β_2 as the shape parameters. All failed pipes are replaced by the end of the failure year.

$$PDF = F(\theta, \beta_1, \beta_2) = \frac{\beta_2}{\beta_1}\left(\frac{\theta}{\beta_1}\right)^{\beta_2 - 1} e^{-\left(\frac{\theta}{\beta_1}\right)^{\beta_2}} \quad for\, \theta \geq 0 \tag{2}$$

For realistic scale and shape parameters, we fitted a Weibull model to the age-dependent survival curve quantiles as elicited from Swiss urban drainage managers, which reflect the time sewers in Switzerland are typically replaced (whether failed or not) (Arreaza 2011). This yields for $\beta_1 = 86.8$, and for $\beta_2 = 2.7$.

Different parameters can be set to explore the effect of sewer life span on transition pathways and performance. As the chosen approach is a cohort-based model (all pipes with a given age have the same probability of failing), we need to 'roll the dice' to identify the fate of a specific pipe. For this, we use a binomial randomiser. The random draws of the randomiser are weighted based on the hazard function or the conditional probability of failure for a pipe that reached the current age of the pipes, following Eq. (3):

$$P(fail\, in\, [\theta, \theta + \Delta\theta]\, |\, not\, failed\, before\, \theta) = \frac{F(\theta + \Delta\theta) - F(\theta)}{1 - F(\theta)} \tag{3}$$

Fig. 3 presents the Weibull distributed sewer deterioration for 100 random samples over 150 years, showing (a) the PDF considering the hazard function and (b) the corresponding cumulative probability of failure.

As the failure distribution depends on the age distribution of the sewer pipes, we also simulate infrastructure maturity. This is done via a '*warm-up*' phase, where we run the deterioration model for a new network (derived from modules 2 and 3) where all pipes start at age 0 and they follow the same stochastic failure model for a period of 130

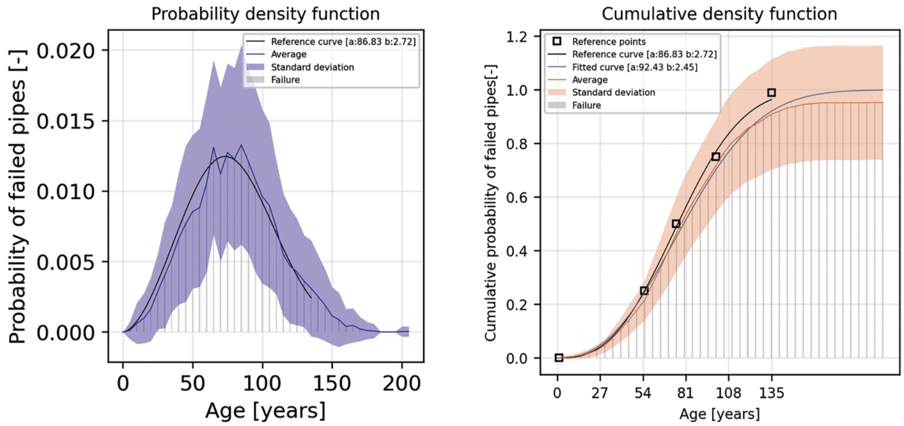


Fig. 3. Weibull distributed sewer deterioration for 100 random samples over 150 years, showing a). the probability density function considering the hazard function and b). the corresponding cumulative density function for the failure model.

years which is the maximum age the pipes can reach. The end of the 130-year warm-up period corresponds to the 'base year'' of simulation for the infrastructure transition pathways (year 0). This allows for a more differentiated pipe age distribution at the base year and accounts for past failures where pipes were replaced in specific city locations. We do not grow the network during the warm-up phase and only replace failed pipes. This warm-up phase gives the network a more distributed pipe age for the start of the simulation. The outcome of this module includes the year and location of the failure of WWTPs and sewer pipes.

3.5. *Infrastructure management strategies module (Module 4)*

This module determines the changes and extensions for the entire wastewater infrastructure following modules 1, 2 and 3 and 'implemented' according to a pre-determined 'infrastructure management' or 'replacement' strategy. The vital underlying rules are:

- All wastewater needs to be managed, either by conveyance or treatment.
- Any treatment plant or sewer pipe failure must be dealt with. It is replaced by new infrastructure with the same or better conditions.
- All measures taken are based on a defined strategy.

Following this, pipes and WWTP are replaced once they have lost their ability to function to the expected standard. This may be due to infrastructure structural or hydraulic failure, as shown in the diagram in Fig. 2. This step changes the infrastructure inventory and triggers costs calculated in the performance evaluation module.

The centralised WWTP is built in the base year (year 0) and assigned an age of zero. For the following simulation timesteps, newly failed pipes (running the failure model from year 0 onwards with parameterisation described in chapter 3.5) and failed wastewater treatment plants are replaced. Decentralised treatment plants (D-WWTP) are constructed depending on the management strategy. Once a WWTP has failed, it is immediately replaced with a new one with age zero and the same treatment capacity (cf. chapter 3.4).

We implemented the following infrastructure management strategies:

A: Replace failed infrastructure with corresponding capacity. When existing pipes or WWTPs do not fulfil the required flow capacity, they must be upgraded to the corresponding dimensions.

B: We implemented a modified deterioration model for WWTPs and replaced all failed infrastructure.

C: Replace all failed infrastructure and pipes with more than 80 % filling ratio (i.e. the ratio between the water depth and the pipe's diameter).

3.6. *Performance evaluation module (Module 5)*

The performance indicators (PI) are used to compare the different transition scenarios. We implemented simplified PIs that enable this direct comparison without having to calculate absolute performance. An example is the hydraulic performance, expressed as deviation from the design performance, instead of using a hydrodynamic model to calculate overflows. In the following, we present the PI for structural vulnerability, hydraulic performance and costs.

3.6.1. *Structural vulnerability*

The network's structural vulnerability in Eq. (4) represents the degree of vulnerability to infrastructure failure for the total amount of pipes $P \in \mathscr{P}$ and WWTPs $W \in \mathscr{W}$ in the sewer system. The index combines the conditional probability of failure F, given the age of each asset as described in Eq. (3), and the hazard exposure, in terms of the total PE that every pipe $p \in \mathscr{P}$ and every WWTP $w \in \mathscr{W}$ provide service to. The resulting index provides a comprehensive and quantitative assessment of vulnerability, which can be used to guide decision-making and prioritise future interventions.

$$\textit{Structural vulnerability} = \frac{1}{P}\sum_{p=0}^{P} F_p * PE_p + \frac{1}{W}\sum_{w=0}^{W} F_w * PE_w \tag{4}$$

3.6.2. *Network's hydraulic capacity*

In terms of the network's hydraulic capacity, we consider the current flow in each pipe $p \in \mathscr{P}$ relative to its maximum capacity as a proxy for sedimentation risk (over-capacity) or flood risk (under-capacity) assessments (see Fig. 4). The overall network's over- and under-capacity can be calculated for each management strategy, whether a centralised or decentralised approach. This information can provide insights

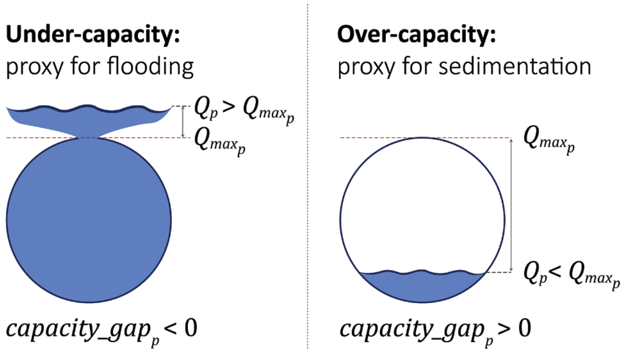


Fig. 4. The visualisation of the PI for under- and over-capacity in sewer pipes.

into how the different strategies are impacting the hydraulic capacity of the network and might therefore contribute to more flooding or sedimentation-related problems.

Eq. (5) calculates each pipe's *capacity gap* between the actual flow Q_p in a pipe in [$m^3 \bullet s^{-1}$] relative to its maximum capacity Q_{max_p} in [$m^3 \bullet s^{-1}$]. The maximum capacity of the pipe gives a sense of the dimensions of the pipes and its impact in case of flooding/sedimentation problems. A larger pipe has a larger impact since more people could be affected. A negative capacity gap means the pipe has under-capacity, increasing the overflow or flooding potential. The overall networks' under-capacity considers all pipes with a negative capacity gap and is calculated using Eq. (6). In contrast, pipes with a positive capacity gap have over-capacity, which can result in sedimentation and related issues (such as clogging or smell). The networks' over-capacity is calculated using Eq. (7).

$$capacity\_gap_p = 1 - Q_p \Big/ Q_{max_p} \tag{5}$$

$$under - capacity = \begin{cases} \dfrac{\sum_{p=0}^{\mathscr{P}} capacity_{gap_p} * Q_{max_p}}{Q_{Network_{max}}} & \forall\ capacity_{gap_p} < 0 \\ 0 & otherwise \end{cases} \tag{6}$$

$$over - capacity = \begin{cases} \dfrac{\sum_{p=0}^{\mathscr{P}} capacity_{gapp} * Q_{maxp}}{Q_{Networkmax}} & \forall\ capacity_{gapp} > 0 \\ 0 & otherwise \end{cases} \tag{7}$$

The overall network's capacity can be interpreted as the remaining capacity in the sewer network since Q_{max_p} relates to the size and volume of every pipe. We calculate the network's remaining capacity using Eq. (8), where $Q_{Network_{max}} = \sum_{p=0}^{\mathscr{P}} Q_{max_p}$ is the maximum design capacity of the whole network in [$m^3 \bullet s^{-1}$].

$$Network's\ remaining\ capacity = \frac{\sum_{p=0}^{\mathscr{P}} capacity_{gap_p} * Q_{max_p}}{Q_{Network_{max}}}$$

$$Network's\ remaining\ capacity = 1 - \frac{\sum_{p=0}^{\mathscr{P}} Q_p}{\sum_{p=0}^{\mathscr{P}} Q_{max_p}} \tag{8}$$

A positive value represents over-capacity, indicating that the closer the index is to 1, the emptier the pipes are, and consequently, the higher the risk of sedimentation. A negative network capacity value signifies that at least one pipe is under-capacity, and the larger the magnitude of the negative value, the more overflow potential there is. A network capacity of zero represents a network with perfect design specifications.

We assume that WWTPs function independently of the sewer network and can handle their inflows. Therefore, only the pipes are considered in this PI.

3.6.3. Costs

The net present value (NPV) analysis is a reliable and frequently employed method. It calculates how much money must be retained to cover all costs over the planning horizon. The cheaper the option, the better (Maurer 2022). We used the NPV to create an overall indicator that characterises the overall cost of a specific strategy for a given planning horizon $T \in \mathscr{T}$, using a discount rate r of 0.02 yr^{-1} (Maurer and Herlyn 2006), as shown in Eq. (9). The overall costs comprise capital and operation & maintenance expenditures (CAPEX and OPEX) of both sewer pipes and WWTPs at every time step $t \in \mathscr{T}$. Be aware that in this implementation, all costs are expressed as positive numbers, while benefits are negative.

NPV = Present value of costs + Present value of benefits.

$$NPV = book\_value_{t_0} + \sum_{t \in \mathscr{T}} (CAPEX_t + OPEX_t) * (1+r)^{t-t_0} - book\_value_T * (1+r)^{T-t_0} \tag{9}$$

To capture the boundary conditions (start and end of the planning horizon), we use linear depreciation to assess the 'time' or 'book' value for both pipes and WWTPs at the start and end of the planning horizon. In other words, we assume that all the existing infrastructure is bought at the beginning of the planning horizon and sold at the end at the given time value. This is done to allow for a fair comparison between wastewater systems given the different lifespans of infrastructure assets. The linear depreciation is based on the lifespans of the infrastructure, which corresponds to the median age of the deterioration model (module 3). The detailed equations to compute the CAPEX, OPEX and remaining book value are described in the appendix (chapter A.3.2).

4. Demonstration of *TURN-Sewers* with an illustrative example

4.1. Catchment definition

An illustrative example demonstrates the capabilities of the above-presented modular model. The catchment is a 400 ha area of 10×10 blocks measuring 200 m by 200 m each, as illustrated in Fig. 5. It is situated next to a lake receiving water from the centralised wastewater treatment plant, treating primarily residential, commercial, and a few industrial waste flows. The assumed characteristics reflect an urban catchment with an average population density of 1112 $PE \bullet ha^{-1}$. The data representing the illustrative example is also provided on the *TURN-Sewers* repository.

4.2. Urban development dynamics

The new wastewater service areas over time are derived from the urban dynamics, land use classification and densification of the city. The spatial wastewater production in the initial setting (year 0) and the changes over time, shown in Fig. 5, hint at the urban densification and expansion. On the first row of maps from year 5 to year 20, we can see that most areas of the city have an increase in population (and therefore wastewater production), not only in new urbanised areas but also in existing parts of the sewer network. In average each block receives about 50 $PE \bullet ha^{-1}$ every 5 years. The total served population, including the contributions from residential, industrial and commetial areas, grows with a rate of 2 % from 191 493 PE in year 0 to 284 576 PE in year 20.

Old infrastructures and blocks with existing wastewater management (WWM) services are presented in grey. New infrastructure is coloured according to the legend. For this example case we have a WWM expansion of 9, 5, 6 and 3 blocks for years 5, 10, 15 and 20.

4.3. Sewer network layout and treatment allocation (Outcome 1)

As demanded by the urban development dynamics, the catchment is changing over time. Fig. 5 presents the development of the sewer network infrastructure and the construction of new wastewater treatment plants for the five-year time steps for the centralised and decentralised expansion strategies (the last two rows in Fig. 5). Both system layouts start with the same centralised WWTP serving the whole population. For the centralised layout, the sewer system grows from 14.9 km to 21.3 km (subfigure 'Centralised layouts' in Fig. 5). In the decentralised layout, the network length remains constant while 23 new small-scale WWTPs appear over time to provide service to newly developed areas (subfigure 'Decentralised layouts' in Fig. 5). The centralised WWTP remains in place to treat wastewater from the sewer areas.

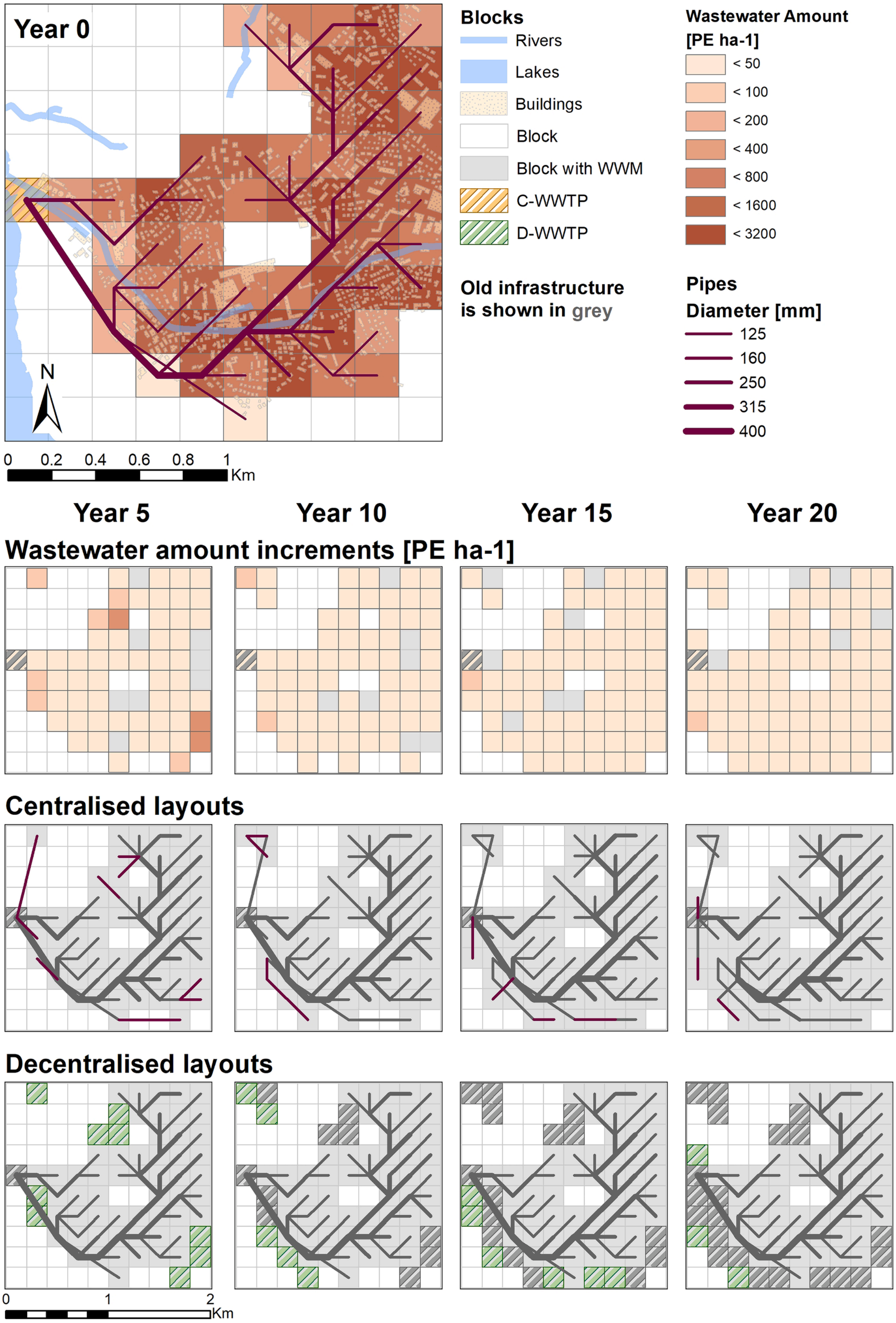


Fig. 5. Urban and sewer infrastructure development for a small urban catchment. New wastewater service areas are based on the PE increments for each simulation year. These new areas can develop with a centralised approach (sewer network expansion through pipe addition and upsizing) or a decentralised approach (disconnecting blocks from sewers and adding new small-scale WWTPs). The grey shaded blocks in the background of the centralised and decentralised layouts represent areas where wastewater management (WWM) needs to be provided by connecting with a pipe or installing a WWTP.

4.4. Hydraulic design (Outcome 2)

Wastewater contributions from different activities range from 1 600 PE•ha^{-1} to 3 200 PE•ha^{-1} in the city centre and from 50 PE•ha^{-1} to 400 PE•ha^{-1} in the outskirts. In Fig. 5, newly built pipes for each simulation year are highlighted in red and the pipe diameters (the thicker the line, the larger the pipe diameter). Since we only consider sanitary flows, neglecting stormwater, we can use small pipe diameters from 0.125 m to 0.4 m.

For urban areas with low population density, especially in most upstream pipes, reduced flows might cause hydraulic problems for not meeting the minimum velocity requirements. This can result in the accumulation of sediments and sulphides in sewer pipes (Penn and Maurer 2021). In the example case, no pipe needed to be upsized from its original design. This suggests that the sewer system was originally designed with sufficient capacity – or due to minimal size requirements with substantial overcapacity – to accommodate growth.

Lastly, Fig. 5 also shows the addition of new small-scale WWTPs over space and time for the decentralisation strategy. The capacity ranges from 200 PE to 1 600 PE per 4 ha block (50 PE•ha^{-1} up to 400 PE•ha^{-1}).

4.5. Failing infrastructure (Outcome 3)

Fig. 6 presents the failures in sewer pipes and wastewater treatment plants over the 20-year simulation period. For the example case, there are 21 failed pipes and no failed WWTP for centralised and decentralised strategies. Since the failure of WWTPs depends on their lifespan and the simulation period is shorter, we do not see any failed WWTP in this example.

Since the centralised and decentralised systems expand differently – the first with pipes and the second with small-scale WWTP – they have different numbers of pipes. Therefore, reproducing with a stochastic model the same failure sequence and location across both strategies becomes challenging. Running multiple simulations can help to range the possible outcomes and reduce the impact of random variations in the model, which ultimately improves the accuracy of predictions and helps decision-makers to develop appropriate management strategies. For this example case, we present a single simulation run with the same failure sequence and location for centralised and decentralised approaches to make a simpler and fair comparison of the PIs in Outcome 5.

4.6. Replacement and upsizing needs (Outcome 4)

In the example case, all failed pipes or treatment plants were replaced, and all pipes or treatment plants with under-capacity were upsized following the basic rehabilitation strategy.

In this example, no treatment plant nor pipe needed to be upsized during the simulation period. Therefore, the replacement was solely dictated by the failure models.

4.7. Performance indicators (Outcome 5)

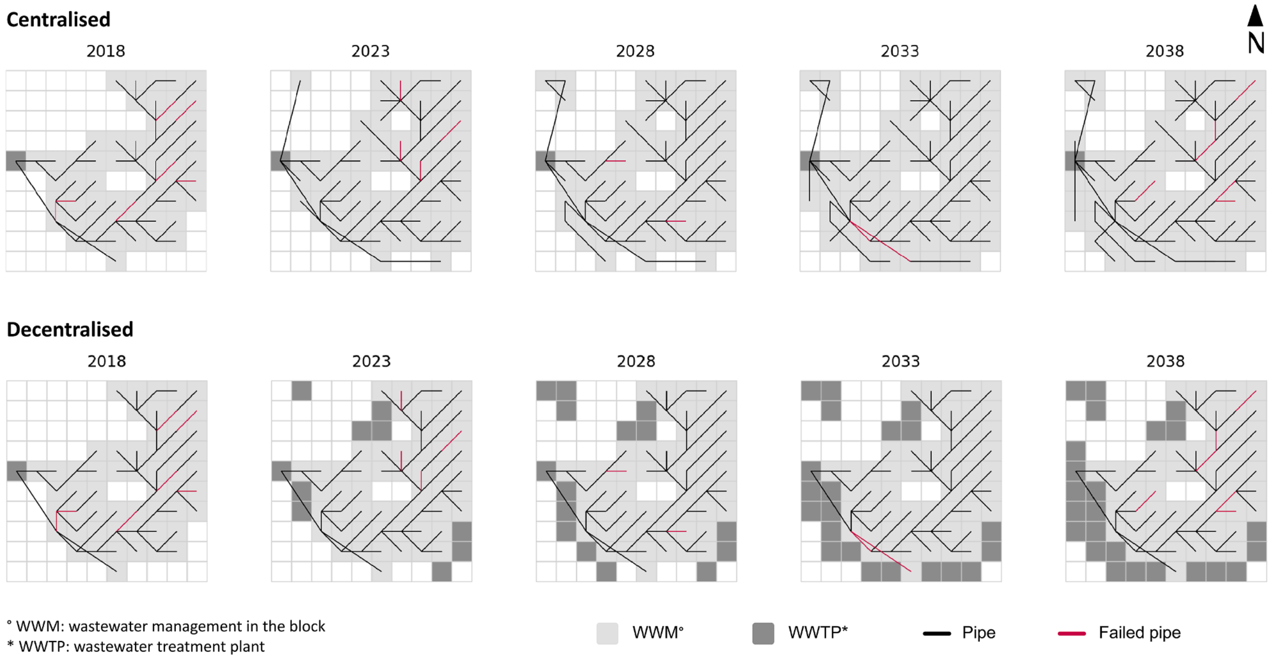
4.7.1. Structural vulnerability

The structural vulnerability for this example case at the end of the simulation period (year 20) is 0.37 for the centralised and 0.38 for the decentralised alternative. Fig. 7 shows the variability of this PI over time. It is highly dependent on the failure process and the age of the infrastructure. At the end of the simulation, the average pipe age is 37 and 48 years, and the average age for the WWTPs is 20 and 14 years for centralised and decentralised systems, respectively. Due to the addition of new pipes to the centralised network, overall the centralised system remains younger and less vulnerable to structural failures. Even though the decentralised system has younger decentralised WWTPs,we cannot perceive much improvement in the system's vulnerability after 20 years of simulation. Without any stochastic variability in the failure process of WWTPs, none of the wastewater treatment plants contributes to the vulnerability index since they are younger than their lifespan (Fig. 8).

The vulnerability of the centralised WWTP is much higher than that of the small-scale WWTP for the same age since it has a higher impact in terms of population equivalents. This means that if the centralised WWTP fails, there is a more significant hazard because more people are affected.

4.7.2. Hydraulic performance

The aggregated system-wide under-capacity, for this case study, remains at zero, which means there is little to no risk for any pipe in the network to present overflows during the 20 years of population development. Therefore, all pipes in the system present over-capacity. The



° WWM: wastewater management in the block
* WWTP: wastewater treatment plant

Fig. 6. Deterioration of wastewater infrastructure over time for a centralised approach (top) and a decentralised approach (bottom).

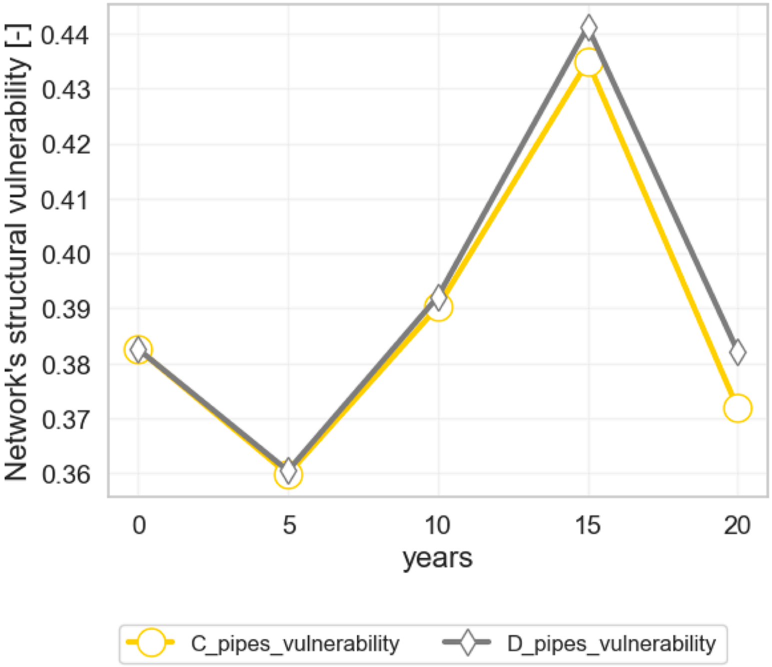


Fig. 7. Structural vulnerability over time for the centralised (C_pipes_vulnerability) and the decentralised (D_pipes_vulnerability) pipes vulnerability.

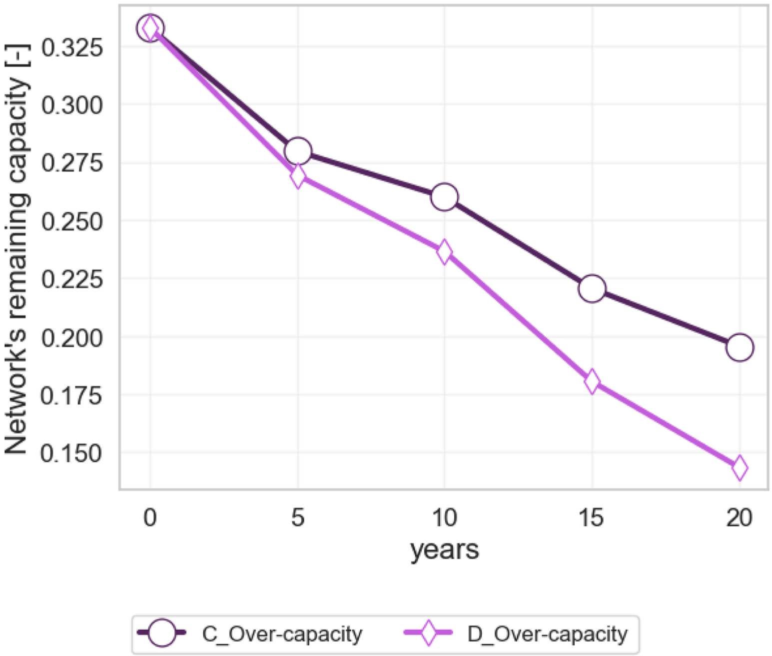


Fig. 8. Hydraulic performance development over 20-years of simulation time related to the network's over-capacity for the centralised (C_Over-capacity) and decentralised (D_Over-capacity) strategies.

aggregated system-wide over-capacity starts at 0.33 (in year 0) for both centralised and decentralised alternatives, which means the network has a remaining capacity on 33 %. During the 20-year development period, there is an increasing population and therefore the systems receives more inflows and reduced its capacity. At the end of the planning horizon (in year 20) the over-capacity drops to 0.20 for the centralised and 0.14 for the decentralised alternatives. This means that over the two decades the decentralisation strategy was better in utilising the spare capacity in the system. These counterintuitive results can be explained by the fact that in the decentralised approach, the existing pipes are getting additional flow from the densification of the existing areas. In contrast, the centralised alternative builds new pipes with a given minimal diameter, hence the new inflows do not reduce as much the over-capacity.

4.7.3. Costs

This module lets us evaluate the cost developments over the planning horizon. At the beginning of the simulation, the system is 'bought' for $160.78 million at the present time value (linear depreciation). At the end of the simulation period, all infrastructure is 'sold' for $42.48 million ($2.63 million for the sewers and $39.85 million for the WWTPs) for the decentralised alternative versus $34.74 million ($5.89 million for the sewers and $28.85 million for the WWTP) for the centralised alternative. The detailed costs resulting from operation and maintenance and expansion, replacement, or upsizing of infrastructure are shown in the appendix (chapter A.3.2) and Fig. 9 as present values, given a discount rate of 0.02 yr^{-1}.

Fig. 9 shows that in both centralised and decentralised alternatives the annual costs are highly influenced by the opex of the centralised WWTP. The main difference between both alternatives comes mainly from the capex of small-scale WWTPs which increases the annual costs of the decentralised approach. Still, after 20 years, the book value of these new WWTPs is also correspondingly higher. For this illustrative example, the net present value (NPV in USD) is $168.60 million for decentralised versus $162.03 million for centralised layouts.

In this example, the NPV for the investments required for decentralisation is close to those for maintaining a centralised strategy, suggesting that decentralisation in new development areas is economically feasible.

4.8. Overall comparison

In Table 1 we summarise the results of different management strategies runs for the same population development and urban characteristics of the catchment area to highlight the possibilities of the *TURN-sewers*. For each management strategy, we present the infrastructure inventory at the beginning of the simulation and the number of pipes and WWTPs replaced over the years. Additionally, we show the PIs regarding structural vulnerability, the network's remaining capacity and the NPV for each management strategy.

In general, we can see that

- a chosen strategy has expected impacts on the PIs and TURN-sewer is able to capture the impacts for such different approaches as conservative replacing above 80 % filling ratio compared with decentralisation.
- the extra costs of the decentralising strategy are not much compared to the overall cost of the wastewater system. This means that decentralised technologies might be a viable systems strategy, especially considering that they also provide other benefits. This

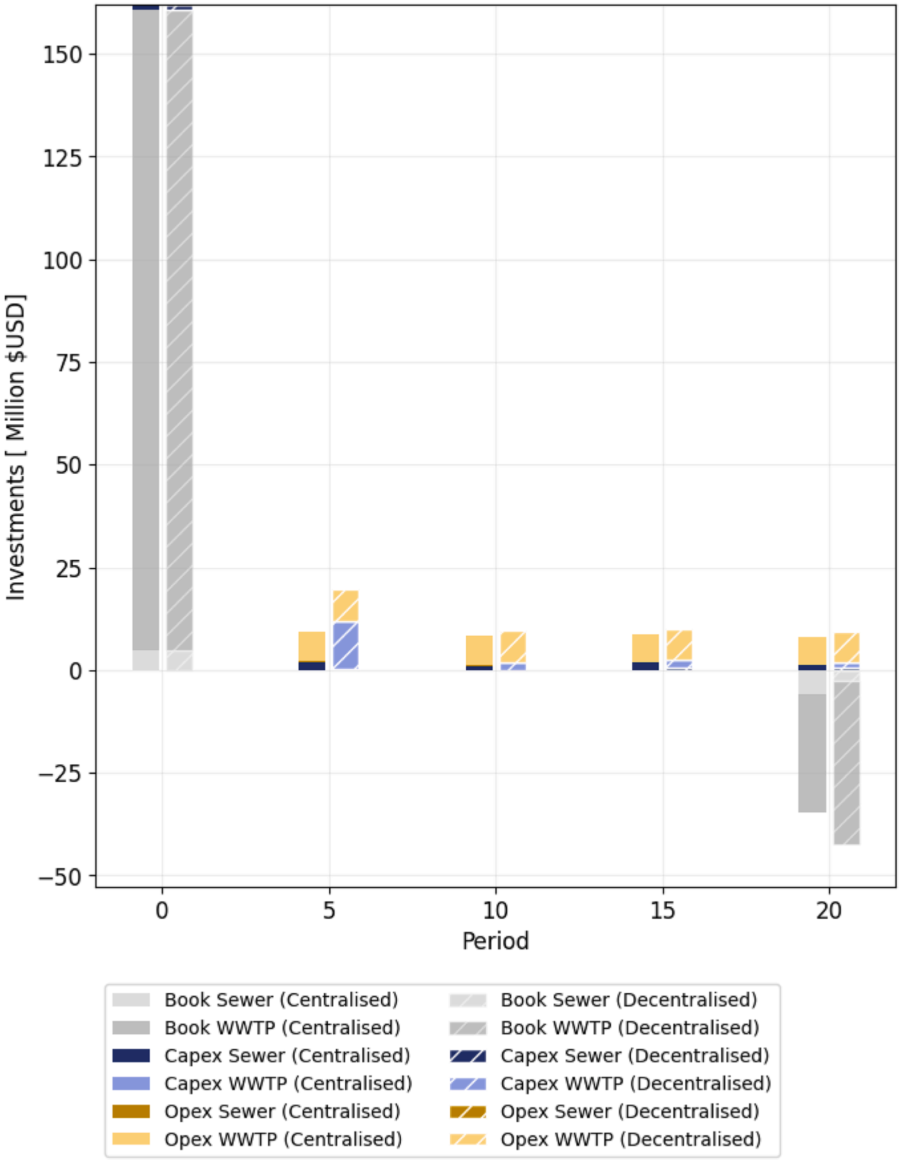


Fig. 9. Investments and book values of wastewater infrastructure over a 20-year simulation period. All assets are 'bought' in year 0 and 'sold' at the end of year 20 at the calculated book value for the corresponding period (see 3.6.2).

Table 1

PI for the different management strategies at the end of the simulation period (year 20).

Management strategy	Centralised	Decentralised
Infrastructure inventory without replacement:		
Total No. of Pipes in year 20	78	55
(New pipes in years 0, 5, 10, 15, 20)	(55, 9, 5, 6, 3)	(55, 0, 0, 0, 0)
Total No. of WWTPs in year 20	1	24
(New WWTPs in years 0, 5, 10, 15, 20)	(1, 0, 0, 0, 0)	(1, 9, 5, 6, 3)
A: Replace failed and under-capacity infrastructure (Example case)		
Infrastructure Failure:		
No. of failed Pipes		
Weibull parameters $\beta_1 = 86.8$ and $\beta_2 = 2.7$	21	21
(Replaced in years 0, 5, 10, 15, 20)	(7, 4, 2, 2, 6)	(7, 4, 2, 2, 6)
No. of failed WWTPs		
Failure at the end of the lifespan	0	0
Performance Indicators (by year 20):		
Average pipe age [years]	37	48
Average WWTPs age [years]	20	14
Network Structural Vulnerability [-]	0.37	0.38
Network remaining capacity [-]	0.20	0.14
Costs:		
NPV [Million USD]	$ 162.03	$ 168.60
B: Replace failed infrastructure with modified deterioration model for WWTPs		
Infrastructure Failure:		
No. of failed Pipes		
Weibull parameters $\beta_1 = 86.8$ and $\beta_2 = 2.7$	21	21
(Replaced in years 0, 5, 10, 15, 20)	(7, 4, 2, 2, 6)	(7, 4, 2, 2, 6)
No. of failed WWTPs		
Weibull parameters $\beta_1 = 15.84$ and $\beta_2 = 6.75$	2	2
(Replaced in years 0, 5, 10, 15, 20)	(0,1, 0, 0, 1)	(0,1, 0, 0, 4)
Performance Indicators (by year 20):		
Average pipe age [years]	37	48
Average WWTPs age [years]	15	10
Network Structural Vulnerability [-]	0.39	0.38
Network remaining capacity [-]	0.30	0.29
Costs:	$ 370.66	$376.37
NPV [Million USD]		
C: Replace failed infrastructure and under-capacity above 80 % filling ratio		
Infrastructure Failure:		
No. of failed Pipes		
Weibull parameters $\beta_1 = 86.8$ and $\beta_2 = 2.7$	21	21
(Replaced in years 0, 5, 10, 15, 20)	(7, 4, 2, 2, 6)	(7, 4, 2, 2, 6)
No. of failed WWTPs	0	0
end of lifespan		
Pipes replaced with capacity above 80 %	62 pipes	58 pipes
(Replaced in years 0, 5, 10, 15, 20)	(1, 11, 11, 19, 20)	(1, 9, 11, 18, 19)
Performance Indicators (by year 20):		
Average pipe age [years]	13	33
Average WWTPs age [years]	20	9
Network Structural Vulnerability [-]	0.37	0.38
Network remaining capacity [-]	0.34	0.32
Costs:	$ 160.14	$ 169.48
NPV [Million USD]		

would justify a more systematic exploration of the decentralisation strategy option space.

- there were not many improvements in the structural vulnerability of the network by using a decentralised approach. The vulnerability is highly dependent on the failure and replacement processes of the different assets.

4.9. Computational efficiency

Table 2 provides an overview of the average computational durations associated with various modules within the *TURN-Sewers* system. The table outlines the time required for data pre-processing and post-processing, the execution time for individual simulation periods and the subsequent output generation. Additionally, it presents the total simulation time for a single iteration across all simulation periods. These computations were conducted on an MS-Windows 10 computer with an IntelCore i7 processor running at 1.61 GHz and 16 GB of RAM.

As we can see from the table, for this example case of 400 ha, each module runs in less than 2.5 s for each simulation period. The runtime of each module increases proportionally with the number of blocks to be designed or analysed, showcasing a linear relationship. By using a simplified generation of the topology and hydraulic design and incorporating specific model assumptions, we can solve the algorithms within a polynomial time complexity.

Since we are producing a map for every single simulation period in every module, the total simulation time of each module is mainly impacted by generating the spatial information output. We did not try to optimise this step and believe there is quite some potential to improve the I/O routines.

5. Limitations and outlook

The results from the exemplary case show the usefulness of *TURN-Sewers* as a simple tool to explore transition pathways of wastewater systems over time. Future work may demonstrate the model in real-world case studies to help engineers and urban planners decide on major systems adaptation. In addition, uncertainty and sensitivity analyses could be conducted to investigate the robustness of the results. The current implementation was kept intentionally as simple and pragmatic as possible, following ‘Occam’s razor principle’. Consequently, it has several limitations that future users might want to overcome.

The *wastewater infrastructure generation module (Module 1)* only considers two types of infrastructure to expand the system. We use either foul sewer pipes for the centralised approach or block-level small-scale wastewater treatment plants for the decentralised approach. Each type of infrastructure is assigned to each block in the new development area depending on the connectivity approach (centralised or decentralised). The combination of centralised and decentralised solutions would be possible from the modelling perspective and it needs to be evaluated in the future to get more robust results. Likewise, deconstruction of previously built infrastructure is also required in future developments to understand the impact of deconstructing existing sewer systems. Additionally, complementing asset types (such as pumps, combined/separate sewers or other decentralisation options) could be added to the model depending on the question. The design approach used for the foul sewer could be easily adjusted for combined sewers by estimating run-off coefficients from the land-use data and utilising design storms.

Module 1 does not need detailed asset inventories and can generate its own infrastructure. Optionally, a specific case’s ‘real’ infrastructure could be used as the initial state. However, in reality, it is very demanding to create a consistent abstraction level – e.g. making a clear distinction between pipes within a block or connecting blocks.

Similarly, the *infrastructure deterioration module (Module 3)* could be fine-tuned to represent the complex factors that would enable to describe more complex management strategies in module 4. Instead of a simple end-of-life approach, a more sophisticated risk-based replacement strategy could be implemented, e.g., based on condition classes. Additionally, rather than handling WWTPs as one unit, a more detailed probabilistic model could distinguish replacement times of assets as mechanical and electrical equipment typically have different lifespans from structural assets.

The most interesting module for adaptation is certainly the *infrastructure management strategies module (Module 4)*. In future work, it would be important also to include the transition of existing centralised infrastructure to decentralised infrastructure, including the dis- or re-connection and respective design adaptations of the system. We also did not accommodate shrinkage scenarios, requiring deconstruction or downsizing of infrastructure. Given that this is a significant problem in economically weak regions in many countries, future research may seek to add such functionality. It needs to be noted that this module contains the creative heart of *TURN-Sewer,* where the key management strategies

Table 2

The average computational time for the example case study under a decentralised design approach showing average run times for each module.

Module	Simulated years [years]	Simulated periods [-]	Data pre-/post-processing per simulation period [s]	Running time per simulation period [s]	Output generation time per simulation period [s]	Total simulation time [s]
Module 1: Infrastructure generation	20	5	1.84	2.29	3.32	29.91
Module 2: Hydraulic design	20	5	1.55	2.45	4.40	56.76
Module 3: Infrastructure deterioration	130+20	31	–	0.60	4.70	163.63
Module 4 : Infrastructure management strategies	20	5	–	0.45	4.72	25.89
Module 5: Performance evaluation	20	5	–	0.02	4.75	24.80

of interest can be encoded and tested against each other.

The performance indicators currently implemented in the *performance evaluation module (Module 5)* are proxies suitable for exploring strategies at a high level of abstraction. However, different performance indicators may be necessary depending on the modelling purposes and the relevant goals of the decision-makers. For example, the hydrodynamic behaviour of the system while undergoing transition could be evaluated using detailed hydrodynamic models for validating the approximate performance results obtained with *TURN-Sewers*. The economic performance does not capture changes in costs over time, which could significantly reduce the cost of high-tech small-scale decentralised treatment solutions (Eggimann et al. 2016b).

However, completely different indicators may be necessary to gain a broader understanding of the social, technical, and environmental benefits of implementing decentralised treatments in existing sewer networks (Lienert et al. 2015; Zheng et al. 2016). Lastly, for a more integrated assessment of the trade-offs between performance dimensions, a multi-criteria analysis could be added to the performance evaluation module (ex-post evaluation) or as a separate module (to inform and drive management strategies affecting other modules).

Finally, users of *TURN-Sewers* may want to expand its functional and analytical capacities by using the modular structure to plug in existing models to address the above limitations or pursue other exploratory modelling questions.

6. Conclusions

We present a modular model, '*TURN-Sewers*', designed for *exploratory transition modelling* of sanitary wastewater systems towards decentralised urban wastewater infrastructure. It can generate future sewer and treatment infrastructure developments in space and time, including layout delineation, hydraulic design, and infrastructure deterioration and rehabilitation. One of the benefits of the modularity of *TURN-Sewers* is that it provides flexibility and allows for easy modification or expansion of the model depending on the exploratory modelling purpose. This model can also be easily updated to accommodate changes in the studied system as new data or knowledge become available, making it a valuable tool for long-term planning and decision-making.

The *TURN-Sewers* model utilises readily accessible input maps, urban land use, and population parameters from an urban development model. It does not require detailed infrastructure data, as it generates its own topology and asset inventory at a user defined abstraction level (block).

Providing decision-makers with a flexible, modular, and efficient city-scale model can provide relevant information about possible transition pathways towards decentralised urban wastewater infrastructure. Despite its relative simplicity, it effectively captures a growing city's key concepts and dynamics. It allows for exploring the effects of different context scenarios on centralised infrastructure configurations that represent current infrastructure and potentials for decentralisation to meet wastewater management goals regarding service provision, cost-effectiveness, and system structural vulnerability.

The simplified generation of the topology and hydraulic design, and the incorporation of specific model assumptions, allow us to solve the algorithms within a polynomial time complexity. Stille input/output routines can be improved to reduce the overall computational effort.

Overall, the proposed methodology offers a practical solution for promoting sustainable wastewater management planning in urban areas.

CRediT authorship contribution statement

Natalia Duque: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lisa Scholten:** Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Max Maurer:** Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The repository with the code and data will be publicly available through the link shared in the manuscript.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121640.

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