When does infrastructure hybridisation outperform centralised infrastructure paradigms? – Exploring economic and hydraulic impacts of decentralised urban wastewater system expansion

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When does infrastructure hybridisation outperform centralised infrastructure paradigms? – Exploring economic and hydraulic impacts of decentralised urban wastewater system expansion

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ABSTRACT

We explore the dynamics of centralised and decentralised wastewater infrastructure across various scenarios and introduce novel insights into their performance regarding structural vulnerability, hydraulic capacity, and costs. This study determines circumstances under which infrastructure hybridisation outperforms traditional centralised infrastructure paradigms. We combined system analysis to map out the modelling problem with the model-based exploration of the transition space using the novel *TURN-Sewers* model. System diagramming was used to identify the parameters or combinations of parameters that significantly influence the performance indicators being assessed. This allowed the creation of relevant simulation scenarios to identify circumstances where a decentralised sewer system could outperform a centralised one. *TURN-Sewers* was applied to model the infrastructure maintenance and generation of new infrastructure over 20 years for a municipality on the Swiss Plateau, considering a population growth rate of 0.03 a^{-1}. Results show that decentralisation in expansion areas with higher densification can outperform the hydraulic performance and structural vulnerability of expanding centralised sanitary wastewater infrastructure. Decentralised systems can also offer economic advantages when capital expenditure costs for small-scale wastewater treatment plants are significantly reduced compared to current costs, particularly at higher discount rates, e.g. reaping effects of economies of scale. The findings of this study emphasise the potential of transition pathways towards decentralisation in urban water infrastructures and the value of models that allow the exploration of this transition space.

1. Introduction

Traditional centralised urban drainage systems, predominate in OECD countries with connection rates above 80% (Eggimann et al., 2015; Larsen et al., 2016; OECD 2023). Sanitary or foul systems ensure the separation of human waste from other wastewater types, facilitating proper treatment and preventing environmental contamination and human health risks. However, centralised systems exhibit drawbacks such as extensive lead times, excess capacity, high initial costs, and limited adaptability, needing comprehensive approaches for effective urban development and climate change mitigation(Maurer 2022). Ageing infrastructure, population growth, urbanisation, and climate change emphasize the need for sustainable and adaptable urban water management systems (Hering et al., 2012).

Resource-efficient decentralised urban drainage systems can offer solutions like on-site wastewater treatment, stormwater management, and source separation of human waste (Guest et al., 2009; Larsen et al., 2016). Decentralised technologies enable efficient layouts and reduced reliance on large-scale investments in centralised infrastructure. The optimal degree of centralisation decreases with increased topographic complexity and urban expansion (Eggimann et al., 2015). Incentives for hybrid or decentralised sanitary wastewater systems include improved hydraulics, enhanced infrastructure resilience, local pollution abatement, ecosystem protection, and resource recovery, driving the transition towards decentralised systems for sustainable and adaptable urban wastewater management (Tchobanoglous and Leverenz 2013; Larsen et al., 2016; Hoffmann et al., 2020; Hesarkazzazi et al., 2022). Transition pathways towards decentralising urban water infrastructures involve

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gradually implementing measures and strategies that facilitate the shift from existing centralised drainage systems to decentralised ones. These pathways include technological, institutional, and policy changes to enhance efficiency, sustainability, and resilience in urban water systems (Maurer 2022).

During the transition from current sanitation practices to adapted systems, including decentralised treatment infrastructure alongside existing centralised networks may be necessary, resulting in hybridisation. This transition arises from the requirements and opportunities presented by growing populations and urbanisation, necessitating the expansion and adaptation of existing infrastructure in new and established urban settlements.

The overarching objective of transition pathways is to identify and establish more adaptable, efficient, and sustainable systems capable of effectively addressing evolving needs and challenges in urban areas. However, empirical evidence shows existing sewer networks have a strong path dependency (Fam et al., 2009; Wolf and Störmer 2010). Consequently, the prevailing centralised approach is propagated, missing the opportunities and changes that its adaptation using decentralised elements might bring. Examples are decentralised wastewater treatment technologies (Sharma et al., 2010; Libralato et al., 2012; Bach et al., 2013; Larsen et al., 2013; Eggimann et al., 2015; Poustie et al., 2015; Larsen et al., 2016; Baron et al., 2017), integration of water reuse and recycling systems (Larsen et al., 2009; Larsen et al., 2013), or the implementation of green-blue infrastructure for stormwater management (Nguyen et al., 2022).

Existing modelling approaches considering hybrid systems typically assume green-field conditions and overlook the presence of pre-existing infrastructure (Eggimann et al., 2015) or provide a static snapshot that fails to account for changes over time. Moreover, these models primarily focus on average costs as the primary determinant, neglecting other technical or environmental assessments (Maurer 2022). See also the overview of existing modelling approaches in Duque et al. (2024).

In (Duque et al., 2024), we propose a modular model to explore the transition from centralised wastewater infrastructure towards more decentralised systems in urban areas, named *TURN-Sewers*. The model allows for comparing different management strategies for sanitary wastewater infrastructure at the city scale. It can generate different system alternatives to adapt the sewer infrastructure (pipes and WWTPs) over time, the so-called '*transition pathways*'. The adaptations are evaluated in centralised and more decentralised (or hybrid) sanitary wastewater systems. The model considers urban expansion and densification over time, which is given as input information.

TURN-Sewers includes independent modules that simulate the generation, dimensioning, deterioration, management, and calculation of performance indicators for different wastewater systems. By utilising readily available spatial information, it can support infrastructure planners and stakeholders in exploring transition pathways and assessing decentralised wastewater infrastructure's economic, hydraulic, and structural impacts. The model's modularity enables it to be easily modified and extended and can be updated with new data or modules. This makes *TURN-Sewers* a valuable tool for long-term planning and decision-making in sustainable wastewater management.

Planning horizons commonly range from 20 to 50 years or even longer. This extended period allows for considering infrastructure investments, maintenance and rehabilitation needs, and implementing sustainable and resilient water management strategies. To effectively assess system performance, we need to consider various management strategies, development scenarios and their combinations for our exploratory modelling purpose. This results in a multitude of transition pathways and potential interactions to consider. Sensitivity analysis, particularly computationally demanding global sensitivity analysis methods, is commonly used to address these complexities (Dimov and Georgieva 2013).

However, much of the extensive computational efforts are often unnecessary, as the primary interest is not in quantifying input-output uncertainty but in understanding the conditions under which an existing centralised system would benefit from hybridisation. The focus should be on identifying parameters highlighting the differences between both systems, potentially maximising these distinctions using quantitative analytical methods.

One such methodology is system diagramming (Enserink et al., 2022). This offers a structured and visual approach to understanding complex systems by mapping out contextual variables' and input parameters' significant causal influences. This understanding enables the exploration of different what-if scenarios (or cases) and helps anticipate the consequences of potential changes or interventions in the system.

A system diagram's visual representation summarises a system's essential components and their relationships. This qualitative analysis helps understand the effects of contextual factors (e.g. means and external factors) on other internal factors of the system, which affect the goals and respective measurement criteria we want to assess (Montibeller and Belton 2006).

This paper aims to determine if and under which conditions wastewater infrastructure hybridisation at the city scale might be preferable over the current centralised infrastructure. *TURN-Sewers* is used to explore multiple management strategies for transforming existing sanitary (foul) sewers towards decentralised or hybrid systems in a typical Swiss city with about 32 000 inhabitants. To make this exploration more systematic, we created a system diagram to identify relevant combinations between contextual factors, management strategies and performance indicators.

2. Methodology

2.1. TURN-Sewers model

TURN-Sewers is a modular model for exploratory transition modelling of sanitary wastewater systems presented in detail in (Duque et al., 2024). It encompasses five modules for the (i) topology generation and (ii) dimensioning of wastewater infrastructure (sewer mains and WWTPs), (iii) the infrastructure deterioration and (iv) management strategies for the expansion of infrastructure as well as re-dimensioning and replacement of failed infrastructure and (v) performance evaluation regarding the structural vulnerability, hydraulic capacity and costs of decentralised alternatives.

To generate the development of sewer expansion over time, the topology and dimensioning of the sanitary sewer infrastructure are based on the urban characteristics of the city (i.e., land use mix, population density, and existing infrastructure). Sanitary sewer infrastructure is placed in blocks with current population density or employment. Based on the wastewater production per block, the sewer network is dimensioned using the Pipe-by-Pipe algorithm (Duque et al., 2022). This algorithm gives the first feasible hydraulic design with a low computational effort. For this model, we kept the hydraulic constraints and the set of available commercial diameters to dimension the sewer pipes constant.

We made several assumptions to build realistic population and urban development scenarios where to contrast the development of a sewer network over time using a centralised versus a decentralised approach to connect all the new areas of the city that require sanitary wastewater management. Key parameters regarding the urban space development and, therefore, the population distribution criteria were kept constant, as well as the criteria for the spatial allocation of decentralised wastewater treatment plants.

2.2. System diagramming

The main purpose of a system diagram, as shown in Fig. 1, is to provide an overview of the problem situation of the system being analysed (Enserink et al., 2022). It has six main components that help to describe the system:

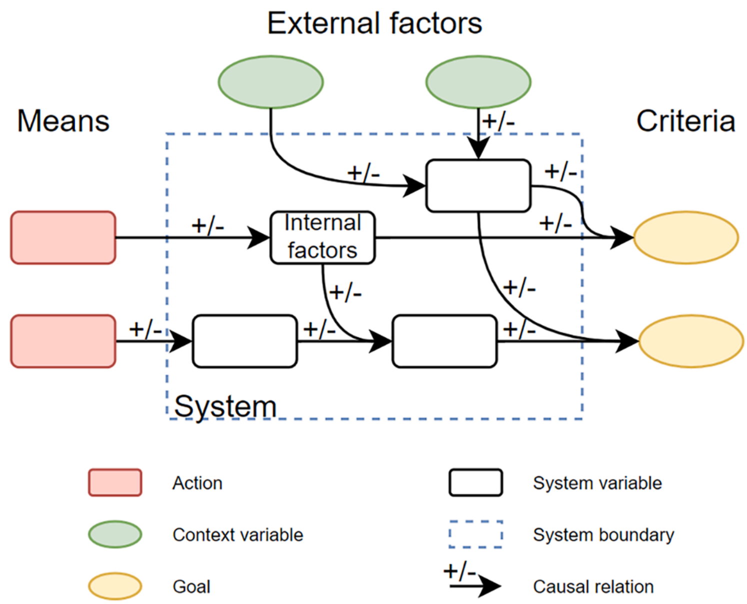

Fig. 1. System diagram components (see Section 2.2 a description of what these entail). Adapted from Enserink et al. (2022).

i. *System boundaries* define the problem demarcation and help define the level of analysis.
ii. *Criteria* describe the measurable indicators used to reflect relevant goals and objectives, given the perceived problem and system boundaries.
iii. *External factors* represent the context variables that influence the different system components.
iv. *Means* describe the action that can affect the system and generate changes in the criteria.
v. *Internal factors* represent the system variables relevant for generating changes in the system and can be influenced by the means, the context variables, other internal factors or even the criteria.
vi. *Causal relations* between all the beforementioned components from i. to v. that map cause-effect relationships of the system that influence the criteria of interest. Each causal relationship can be labelled with a positive (+) or negative (-) sign to indicate the direction of influence between factors X and Y. `A '+' to denote that if the value of Y increases, the value of X will also increase (positive correlation), or a '–' to denote that if the value of Y increases, the value of X will decrease (negative correlation).

To build the system diagram, we started with a 'means-ends diagram' to establish the problem boundaries, means (actions, here causes that can be meaningfully influenced) and criteria (the effects of interest). This will help to determine an appropriate level of analysis.

From this, we built a more extensive 'causal map' to illustrate the relationships between relevant factors (or variables) concerning the problem and system of interest. We performed a causal analysis to comprehend how changes in one factor led to changes in other factors. This process requires reasoning backwards from each PI to all factors influencing them. For more details on constructing a system diagram, see (Enserink et al., 2022). This qualitative analysis helps us understand the effects of means (infrastructure management strategies) and external (context) factors on internal factors that ultimately affect the criteria (Montibeller and Belton 2006).

2.3. Boundaries of the system of interest and case study

Given the aims of this study, we are interested in the desirability of wastewater infrastructure hybridisation as a means to deal with dynamic population and land use changes as an alternative to the current centralised infrastructure management paradigm. The catchment area is situated on the Swiss plateau and encompasses an area of 37.69 km^2 dischaging towards a single WWTP (Fig. 2). This area has a population of 31 827 people in year-0 (corresponding to 2018). The urban land use is predominantly residential, with an average housing density of 5 dwellings per hectare (= 100 m × 100 m). The physical topography is characterised by hilly areas in the northeast (lowest and highest block average elevation 439 and 462 m.a.s.l., respectively), a river system and a less steep area closer to the lake to the southwest, representing various topographical characteristics. Both municipalities are surrounded by green spaces (agriculture, parks and gardens or forests) or undeveloped areas, which might become urbanised in the future and assigned residential, commercial, or industrial land use, given population pressure and proximity to the city of Zurich (the most significant urban agglomeration in Switzerland).

2.3.1. Initial topology based on topography, land use and population density

Input data for the topography, population density and land use come from open data repositories from Swisstopo (2018). We used a 10 m resolution digital elevation model. Population density and land use were

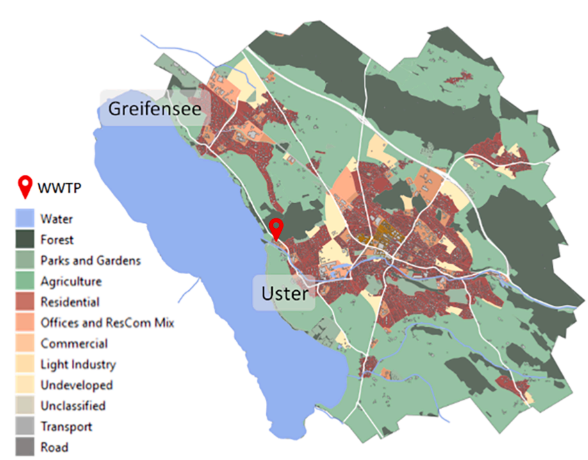

Fig. 2. Land use classification for the case study area in year-0 (i.e. the beginning of the simulation period).

classified according to UrbanBEATS classification (Bach et al., 2015) and converted to a 10 m × 10 m raster for UrbanBEATS input. Additionally, spatial data of roads and rivers were obtained in ESRI Shapefile format to aid the delineation and network generation. The baseline for the assessment was 2018 (year-0), with land use and population data from this period.

The spatial land use abstraction was created for a 200 m × 200 m block size. The wastewater discharge per block is calculated from the assumed water consumption per block, considering the land use mix and population density. Areas with higher discharge are those with a high density of residential, commercial, and industrial areas.

2.3.2. Initial hydraulic design

The initial hydraulic design is based on the design guidelines that are kept constant for this system's analysis, and the design flow is based on the wastewater produced in the study area. The hydraulic design of the foul sewers follows the design guidelines proposed by Duque et al. (2022), following the Pipe-by-Pipe design algorithm. The average water demand per capita is 200 L day^{-1}, with an average daily peak factor of 1.2.

The design of the wastewater treatment plant assumes that in year-0 the 'real' future growth in demand is unknown and needs to be assumed. Generally, we used an assumed design growth rate of 0.01 a^{-1}. While centralised WWTPs collect the load of all upstream pipes, decentralised WWTPs only receive their block's contribution.

The load per block in [PE] is used for dimensioning WWTPs, while the pipes are dimensioned based on their daily peak flow.

2.3.3. Initial sewer age distribution

To incorporate the age distribution of sewer pipes into the infrastructure failure model, we simulate the infrastructure ageing with the given deterioration model. This involves running the deterioration model over a "warm-up" phase before starting the simulation period for infrastructure transition planning. During this phase, the network does not expand; only failed pipes and WWTPs are replaced. This leads to a more varied pipe age distribution at the start of the simulation, accounting for past failures and replacements in specific locations within the sewer catchment.

2.4. Criteria and performance indicators

The main objectives are related to good structural condition, good hydraulic performance, and low system costs. For each objective, a measurable criterion, hereafter performance indicator (PI), was defined to track performance on the objective over time using a 5-year time step for the urban development simulation. For details on how to compute each PI, please refer to Duque et al. (2024). These PI help to compare the performance of centralised versus decentralised approaches.

2.4.1. Structural vulnerability

The structural vulnerability criterion aims to quantify the vulnerability to infrastructure failure in the sewer system. We defined a performance indicator that considers the total amount of pipes and wastewater treatment plants (WWTPs) in the system, denoted as P and W, respectively. It combines the conditional probability of failure F for each asset, given its age (described in Eq. (1)), with the hazard exposure associated with the total population equivalents served by each pipe p and each WWTP w.

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

2.4.2. Network's hydraulic capacity

The network's remaining capacity provides insights into the hydraulic capacity of the network and its potential flooding or sedimentation-related issues. It considers the actual flow in each pipe Q_p relative to its maximum capacity Q_{max_p}. We decided to define an indicator that reflects the 'capacity gap' in terms of the entire network's remaining capacity, calculated according to Eq. (2).

$$Network's\ remaining\ capacity = 1 - \frac{\sum_{p=0}^{\mathscr{P}} Q_p}{\sum_{p=0}^{\mathscr{P}} Q_{max_p}} \tag{2}$$

The wastewater produced is calculated based on water consumption patterns considering the population and land use in the specific area of the city. Following the modelling of urban dynamics and spatial development of the sewer system is described in more detail by Duque et al. (2022).

2.4.3. Costs

Costs are evaluated for construction or rehabilitation and operation and maintenance of the infrastructure. The specific cost models used depend on the component being analysed.

2.4.3.1. Sewer network. Eq. (3) shows the capital expenditures for the construction or replacement of single pipes, $CAPEX_p$. Variables are the average excavation trench $depth_{avg}$, the cost factor $f_c = 1.2$ and parameters c_1 and c_2 are functions of the diameter d. The annual operating expenditures, $OPEX_p$, per linear metre for a single pipe is \$3.6 $m^{-1}a^{-1}$ (VSA 2011; Eggimann et al., 2015).

$$\begin{aligned} CAPEX_p &= \left(c_1 * depth_{avg} + c_2 * f_c\right) L \\ c_1 &= 152.51 * d + 173.08 \\ c_2 &= 760.31 * d - 78.21 \end{aligned} \tag{3}$$

2.4.3.2. Wastewater treatment plants. Cost of high-tech treatment facilities, C_{WWTP}, are a function of the load to be treated in PE and follow Eq. (4). This simple scaling function is applied to both $CAPEX$ and $OPEX$ of centralised or decentralised WWTPs, using the corresponding parameters a and b as presented in Table 1 (VSA 2011; Eggimann et al., 2015).

$$C_{WWTP} = a(PE)^b * PE \tag{4}$$

2.4.3.3. Costs of one system alternative. $total_{investmets_t}$ in Eq. (5) considers the total capital expenditure (Eq. (6)) and operation and maintenance costs (Eq. (7)) of all sewer pipes $p \in \mathscr{P}$ and WWTPs $w \in \mathscr{W}$, at a specific time $t \in \mathscr{T}$.

$$total_{investmets_t} = CAPEX_t + OPEX_t \tag{5}$$

$$CAPEX_t = \sum_{p \in \mathscr{P}} CAPEX_p + \sum_{w \in \mathscr{W}} CAPEX^C_{WWTP_w} + CAPEX^D_{WWTP_w} \tag{6}$$

$$OPEX_t = \sum_{p \in \mathscr{P}} OPEX_p + \sum_{w \in \mathscr{W}} OPEX^C_{WWTP_w} + OPEX^D_{WWTP_w} \tag{7}$$

2.4.3.4. Net present value (NPV). We used the net present value (NPV) method to create an overall indicator that characterises the overall cost of a specific management strategy for a given planning horizon T and a

Table 1
Replacement and operation and maintenance (O&M) cost parameters for centralised (large-) and decentralised (small-scale) wastewater treatment plants categorised by population equivalents (PE).

	Connectivity	C_{WWTP}	a [-]	b [-]
CAPEX	Centralised*	$CAPEX^C_{WWTP}$	7137.20	− 0.195
	Decentralised**	$CAPEX^D_{WWTP}$	9512.80	− 0.209
OPEX	Centralised	$OPEX^C_{WWTP}$	380.09	− 0.204
	Decentralised	$OPEX^D_{WWTP}$	243.45	− 0.171

* Centralised WWTP are large-scale treatment plants for more than 5 000 PE.
** Decentralised WWTP are small-scale treatment plants for less than 5 000 PE.

discount rate r (see Eq. (8)). As we mainly consider costs, a positive NPV indicates expenditures. Lower NPV indicates lower costs and, therefore, the more favourable a specific option is. If not mentioned otherwise, we generally use a discount rate r of 0.02 a^{-1} (Maurer and Herlyn, 2006).

In order to consider the value of the existing infrastructure at the start and the end of the simulation, we 'buy' the entire infrastructure at the beginning ($book\_value_{t0}$) and 'sell' everything at the end of the planning horizon ($book\_value_T$). We use a linear depreciation based on the lifespan and the replacement value C (Eq. (9)) to identify the book values.

$$NPV = Present\ value\ of\ costs + Present\ value\ of\ benefits$$
$$NPV = book\_value_{t_0} + \sum_{t \in \mathcal{T}} (CAPEX_t + OPEX_t) * (1+r)^{t-t_o} - book\_value_T * (1+r)^{T-t_o} \quad (8)$$

$$book\_value_T = C\left(1 - \frac{age}{lifespan}\right) \quad (9)$$

2.5. External (context) factors

2.5.1. Population growth

In this study, we explored the consequences of decentralisation using an *extreme* case of densification in the case study. We used an exponential growth model, as described by Duque et al. (2024), with an annual growth rate *0.03* a^{-1} over *20* years. The baseline scenario in chapter 3.3, presents the population development over time.

2.6. Means: infrastructure management strategies

To explore the system of interest specified in 2.3, we are considering the main management strategies that drive infrastructure changes and affect the objectives of interest for the case study area. These are infrastructure expansion to service the growing population over the next 20 years and replacing existing infrastructure to avoid or remediate structural or hydraulic failure. Our model considers two main paradigms for system expansion, centralised and decentralised.

The initial status of the system is a conventional centralised system, which evolves based on population development and urban dynamics. If the common practice of centralised wastewater management is propagated, new pipes are connected to the existing centralised sewer network and WWTP. Alternatively, in the decentralised approach, newly developing areas in the case study can be connected to local, small-scale decentralised wastewater treatment plants, for which neither expansion nor adapting of the sanitary sewer mains is needed. Each treatment plant's capacity is designed for the volume of wastewater produced in its urban drainage watershed.

2.6.1. Decentralisation

When assigning decentralised wastewater management to new development areas, we assume that decentralised wastewater treatment plants are assigned to individual 200 m × 200 m blocks, as Duque et al. (2024) defined. Each block represents a sub-catchment draining to its specific treatment plant. The spatial simplification is kept at the block scale. This keeps a consistent model abstraction level and prevents the need to generate spatially explicit sewer connections and networks inside each decentralised block.

We assume a high-tech treatment option for the small treatment plants with an expected end-use quality comparable to the one offered by centralised treatment plants and in line with current treatment standards.

2.6.2. Infrastructure rehabilitation and replacement strategies

The functional and structural state of the pipes and WWTPs in the wastewater infrastructure system and changes in their hydraulic capacity drive the rehabilitation and replacement of these infrastructures. Following this, assets are replaced once they have lost their ability to function to the expected standard, either due to infrastructure structural or hydraulic failure.

2.6.2.1. Structural failure. Estimating sewer structural failure is challenging due to the broader variability of deterioration influenced by local factors. Survival models can approximate the deterioration and likelihood of a failure. However, replacement times often reflect the time when it was considered necessary to replace the asset due to potential hazards, coordinated infrastructure replacements, or regular maintenance, rather than solely when the asset loses its function(van Riel et al. 2016; Tscheikner-Gratl et al., 2019). To estimate sewer failure times, a Weibull model, as described in (Duque et al., 2024). Eq. (10), states the probability of failure F of an asset as a function of the age θ and the scale β_1 and shape parameters β_2.

$$\boldsymbol{F}(\boldsymbol{\theta}, \boldsymbol{\beta}_1, \boldsymbol{\beta}_2) = \frac{\boldsymbol{\beta}_2}{\boldsymbol{\beta}_1}\left(\frac{\boldsymbol{\theta}}{\boldsymbol{\beta}_1}\right)^{\beta_2 - 1} \boldsymbol{e}^{-\left(\frac{\theta}{\beta_1}\right)^{\beta_2}} \ \boldsymbol{for}\ \boldsymbol{\theta} \geq 0 \quad (10)$$

For the sewer pipes, we used a parametrisation based on typical sewer replacement times in Switzerland, regardless of failure (Arreaza 2011). This yields for β_1= 86.8, and for β_2= 2.7. We assume the same Weibull distributed model to simulate the failure of WWTPs with β_1= 21.22, and for β_2= 4.1, assuming that the average failure age is around 20 years.

2.6.2.2. Hydraulic failure. We consider the current flow in each pipe relative to its maximum capacity as a proxy for sedimentation risk (overcapacity) or flood risk (under-capacity) assessments, as explained in chapter 2.4.2. A pipe experiences under-capacity when the actual flow in a pipe in [$m^3 \bullet s^1$] is larger than its maximum capacity in [$m^3 \bullet s^{-1}$]. This might trigger a pipe replacement due to hydraulic failure.

We assume that WWTPs do not have any hydraulic limitations. Therefore, only the pipes are considered in this PI.

2.7. Internal factors and causal relations

The internal factors and causal relations between them are represented by the different modules of *TURN-Sewers* that are relevant for generating changes in the system and can be influenced by changing the model implementation and parameters determining the context variables and management strategies, assuming other internal factors and the PIs as 'fixed'.

2.8. Identification of relevant modelling cases

The resulting system diagram was used to identify relevant mappings between context factors, management strategies and PIs of interest. This involved tracing backwards from each PI and identifying the factors that influenced them the most. Then, for each of these it was determined which combination of parameters would increase the difference between a decentralised or centralised paradigm and favour one over the other. Finally, specific modelling cases and respective parameterisation were derived therefrom.

3. Results

3.1. System diagram and identification of modelling cases

Following the specification of characteristics i-vi in chapter 2.2, the resulting system diagram is presented in Fig. 3. The general system diagram of the model considers the following:

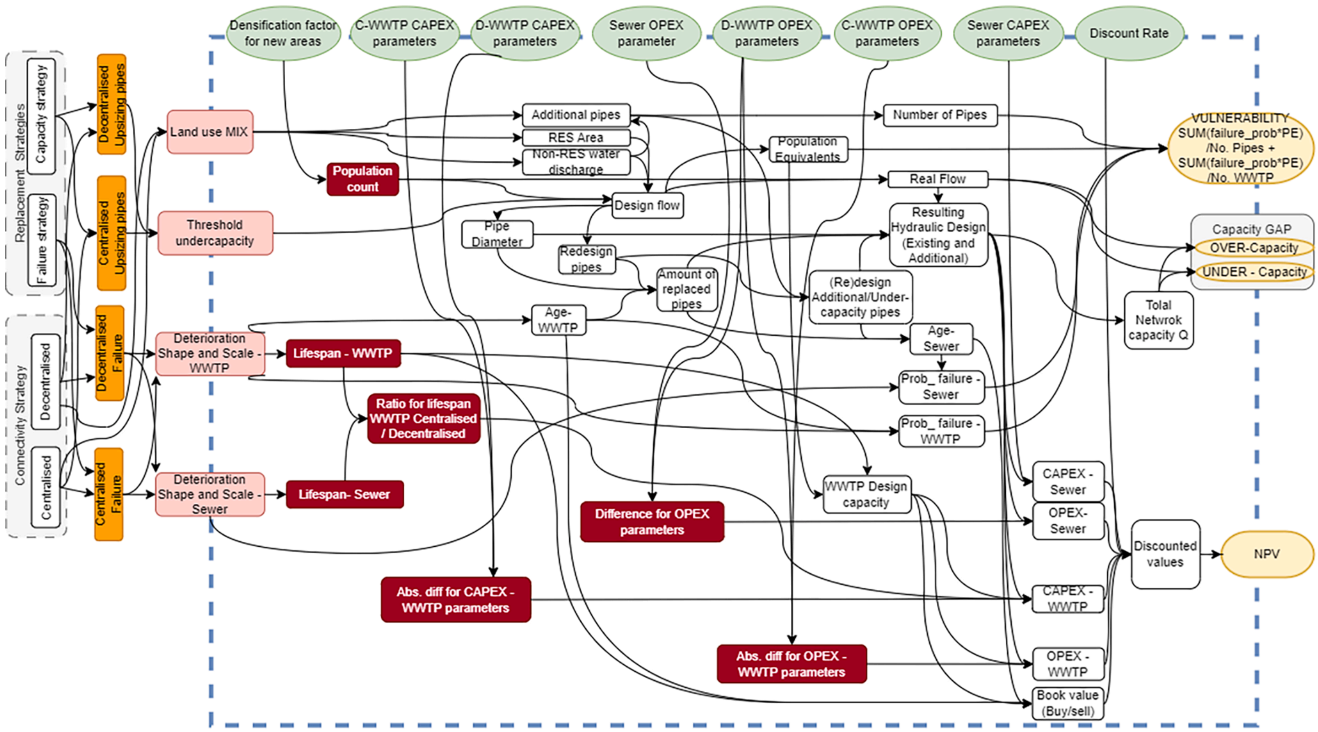

Fig. 3. System diagram for TURN-Sewers Model.

i. *System boundary* considers the initial urban characteristics, such as population, land use and the existing wastewater infrastructure.
ii. *Criteria* shown in yellow on the right present the three PIs that we evaluate regarding the structural vulnerability, the network's hydraulic capacity and the costs.
iii. *External factors* shown in green correspond to population and cost parameters affecting the PIs.
iv. *Means* or actions shown on the left are defined by the management strategies based on infrastructure failure or hydraulic capacity for both centralised and decentralised systems. In concrete, we defined four actions shown in red regarding the land use mix, a threshold to identify pipes with under-capacity, and the shape and scale factor affecting the deterioration model for the sewers and WWTPs.
v. *Internal factors* in white show the relevant variables connecting the means and context variables to other internal factors and the criteria.
vi. *Causal relations* shown using arrows, map the cause-effect relationships within the system.

The individual system diagrams for every single indicator used to identify the modelling scenarios through backward tracing are provided in the Appendix. For instance, the vulnerability PI depends mainly on the wastewater load, the number of pipes, the WWTPs and the probability of infrastructure failure (see Fig. A.1. in the Appendix). Going backwards in the system diagram, we can identify that this PI has a positive relationship with the densification factor for new areas, the ratio between the lifespans of small-scale WWTPs and sewer pipes, as well as the failure process, which depends on the shape and scale parameters of the corresponding deterioration model.

A second example is the network's hydraulic capacity, which is directly linked to the population-generated discharge. It seems to be affected by higher population densities in the city's outskirts (expansion areas). More upstream flow in the centralised approach accumulates downstream and may cause overflows since the existing sewers were not designed for those additional flows. The threshold for the replacement of pipes by hydraulic capacity is also one key factor that, when decreased, might help to improve the overall network's hydraulic capacity (see Fig. A.2. in the Appendix).

As for the costs, almost all parameters influence the final NPV (see Fig. A.3. in the Appendix). However, it is evident in the diagram that the CAPEX and OPEX parameters and the discount rate may be the most sensitive parameters for this PI given their direct causal influence.

3.2. *Selected combinations of context variables, management strategies and respective parameterisations to identify conditions under which hybridisation could dominate centralised expansion on the performance indicators*

In order to analyse the system, we defined a baseline case that describes the boundary conditions of our case study for centralised and decentralised approaches (Chapter 3.3). It designates population growth and urban expansion, defining infrastructure generation and dimensioning. It also specifies the infrastructure deterioration over time under the parametrisation specified in chapter 2.6.2.1.

Based on the system diagram (Fig. 3) and the relevant parameters identified for each PI, we defined six cases to explore the performance of decentralised systems compared to the centralised approach.

Case A considers replacing pipes whose flow exceeds a maximum filling ratio of 80%. This triggers the replacement of pipes before failure for hydraulic reasons. We hypothesise that this negatively affects the costs of centralised systems as it has a greater number of pipes that could be affected.

Case B increases the absolute difference in replacement or construction costs of WWTPs, by decreasing the size-dependant *CAPEX* parameters for small-scale WWTPs, a^{D}_{WWTP}, and b^{D}_{WWTP}. This is based on the assumption that the costs for WWTP package plants might decrease based on economies of scale in a globalised decentralisation push.

Case C increases the absolute difference in operation and maintenance costs between the sewer network and the WWTPs. We increased the $OPEX_p$ parameter for sewer networks by three times while decreasing the $OPEX_w$ for WWTPs a^D_{WWTP} to a fifth of the current cost.

Case D explores the effect of a higher discount rate r of 0.03 a^{-1}– generally one of the most sensitive parameters in cost calculations over time.

Case E assumes the lifespan of WWTPs and sewer pipes to be 50 years. According to the system diagram, the hypothesis is that a higher ratio (closer to 1) between the lifespan of WWTPs and pipes influences the deterioration of the assets and, therefore, substantially impacts all the PIs, especially the structural vulnerability and costs.

Case F increases the population in expansion areas by three times. Based on the system diagram, this influences all PIs unfavourably for the centralised paradigm. As more flows from the expansion areas are drained into the existing system, this may generate overflows and require higher replacement costs if more pipes need to be upsized.

3.3. Baseline case

3.3.1. Wastewater infrastructure generation and hydraulic design

Based on a 0.03 a^{-1} population growth in the catchment area, Table 2 presents the wastewater infrastructure expansion over 20 years. Note that in year-0, centralised and decentralised systems start with identical infrastructures. Afterwards, centralised systems expand only through new pipes, while decentralised systems expand only through small-scale WWTPs. The table shows the number of new pipes, their total length in the centralised approach, the amount of new small-scale WWTPs, and their total design capacity in the decentralised approach.

The centralised WWTP was newly designed at year-0 with a projected capacity of 45 354 PE. Commercial and industrial loads are calculated using a scaling factor to reflect peak flow for non-residential areas. Our current implementation uses a scaling factor of 2.8 for all blocks, a typical peak factor for non-residential areas in Switzerland (Duque et al., 2024).

Fig. 4 presents the wastewater discharge produced in terms of [PE ha^{-1}] in each block over the two decades. In year-0 there are 47.2 PE ha^{-1} on average. New development areas average between 4.8 PE ha^{-1} and 11.62 PE ha^{-1} from year-5 to year-20. Since we do not consider stormwater inflow, we have extremely low flows, which impacts the hydraulic design of the pipes.

94.5% of the pipes in Year-0 have the most minor diameter of 0.125 m, given the very low sanitary flows in the sewer network. Even with the smallest diameters, 78.2% of the pipes work under 20% of the hydraulic capacity.

New wastewater infrastructure is built to give service to urban expansion areas. Fig. 5 shows the wastewater infrastructure development and expansion through space, using (centralised) sewer pipes and (decentralised) small-scale WWTPs, from year-5 to year-20.

Table 2
Urban drainage system expansion. Note that in year-0, centralised and decentralised systems start with the same infrastructure inventory. Afterwards, centralised systems expand only through new pipes, while decentralised systems expand only through small-scale WWTPs.

	Centralised and Decentralised inventory			
	N. Pipes	Length [Km]	N. WWTPs	Design capacity [PE]
Year 0	239	73.1	1	45 354
	Centralised expansion		Decentralised expansion	
	N. Pipes	Length [Km]	N. WWTPs	Design capacity [PE]
Year 5	70	21.3	70	3 255
Year 10	27	6.7	27	1 217
Year 15	36	9.9	36	1 006
Year 20	38	11.3	38	732

3.3.2. Wastewater infrastructure deterioration

Fig. 6 highlights one possible failure process of the sewer pipes and WWTPs along the planning horizon. Both centralised and decentralised approaches start with the same condition and failed infrastructure. In Year 0 the infrastructure failure is based on the current age of each asset in the system, which is defined through a 130-year warm-up simulation of the same deterioration model. This helps to have a better age distribution of the pipes at the beginning of the simulation period. The deterioration process for the following years considers the replacement history. In order to be able to compare the centralised and decentralised approaches, it was necessary to make sure the location of the failure was the same. The replacement costs or impact of failed infrastructure is sensitive to its location in the catchment. Normally, for centralised systems, the closer the pipe is to the outlet of the catchment area, the bigger it is and the more people could be affected in case of a failure.

3.4. System analysis – to decentralise or not to decentralise?

In the following, we compare the performance of both centralised and decentralised approaches under an urban expansion scenario with a population growth rate of 0.03 a^{-1}. Both systems start at the same centralised state (see section 3.3).

3.4.1. Structural vulnerability

Table 3 indicates the structural vulnerability of the network under the different cases. The higher the value the more vulnerable to failure is the infrastructure. In the table we can observe that this indicator is very similar for both centralised and decentralised cases and does not vary much when more pipes are replaced by capacity, as in case A. Decentralised systems seem more beneficial when the population in the newly developed areas gets higher densification than the city centre (old urban areas), as in case F. This case presents the highest difference between the structural vulnerability of centralised and decentralised approaches.

3.4.2. Network's hydraulic capacity

The index is influenced by the size of the pipes that define their maximum capacity, and the actual flow in them. It is also influenced by capacity replacement strategies. A negative capacity gap indicates under-capacity, increasing the potential for overflow or flooding. Conversely, a positive capacity gap suggests over-capacity, leading to sedimentation and related problems. A network capacity of zero represents a network with ideal design specifications.

Table 4 indicates the remaining hydraulic capacity in the sewer network regarding the piped system. In this case study we can see that the sanitary sewer network is functioning with substantial over-capacities due to the minimal diameter required by the design guidelines. In all cases, the decentralised approach utilises the existing sewer system better, as no new pipes are built. In the centralised case the newly built pipes increase this PI even further.

3.4.3. Costs: net present value

The cost index is influenced by almost every system variable and management strategies, as shown in the system's diagram in Fig. 3. Table 5 indicates the NPV for each case and the differences between the NPV of decentralised and centralised approaches. As anticipated, the lower capital expenditure (*CAPEX*) costs for the WWTPs in case B make decentralised systems more appealing for the current case study. This economic advantage becomes more significant at higher discount rates.

4. Discussion

The system analysis provides insights into the performance indicators of centralised and decentralised sewer infrastructure. The findings suggest that decentralisation can be on par or offer advantages under certain conditions. Specifically, higher population density in expansion areas and cost differentials, such as lower CAPEX costs for

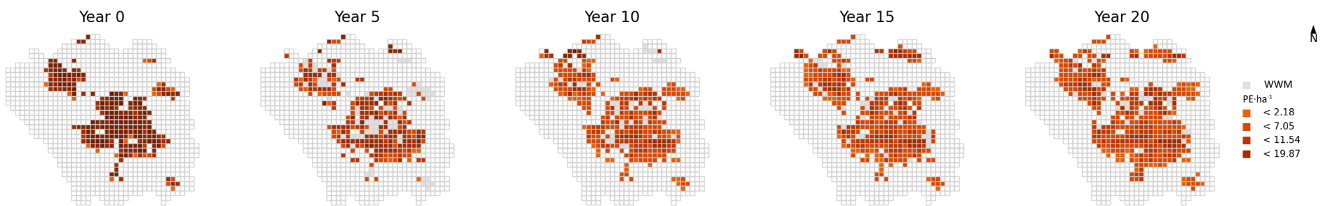

Fig. 4. Wastewater production increments in [PE ha^{-1}] over 20 years of urban development simulation, considering the specific land use mix in each block. This wastewater production applies for both centralised and decentralised approaches. Grey blocks have wastewater management (WWM), but no increment in their wastewater production.

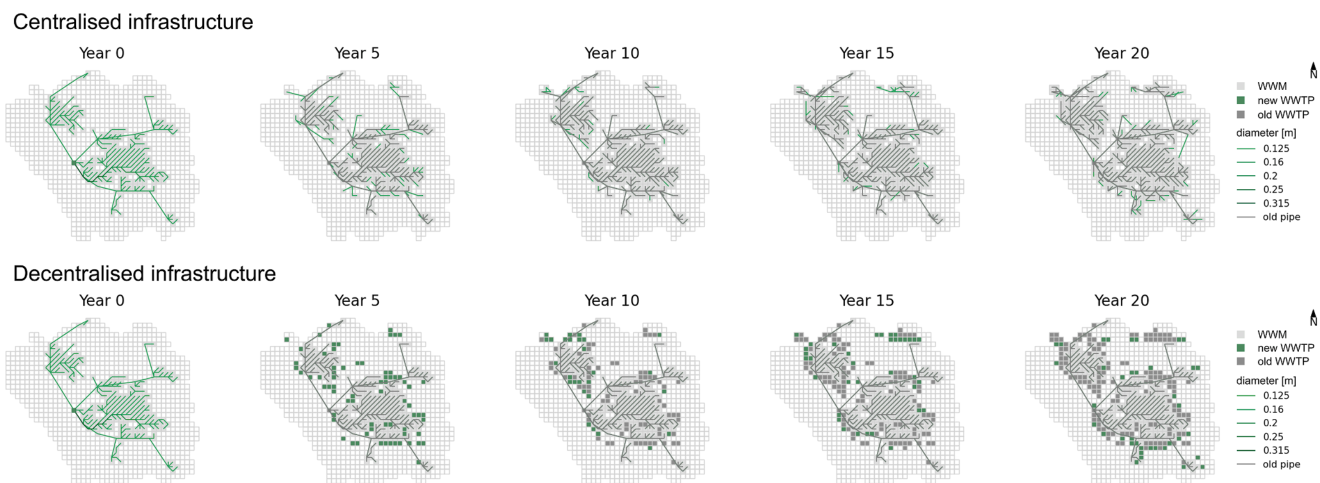

Fig. 5. Wastewater infrastructure expansion to connect the new development areas. The maps include the layout of the sewer pipes and WWTPs and the corresponding hydraulic design for centralised (top) and decentralised (bottom) alternatives in the case study. New infrastructure is highlighted in colour, while old infrastructure appears in grey. .

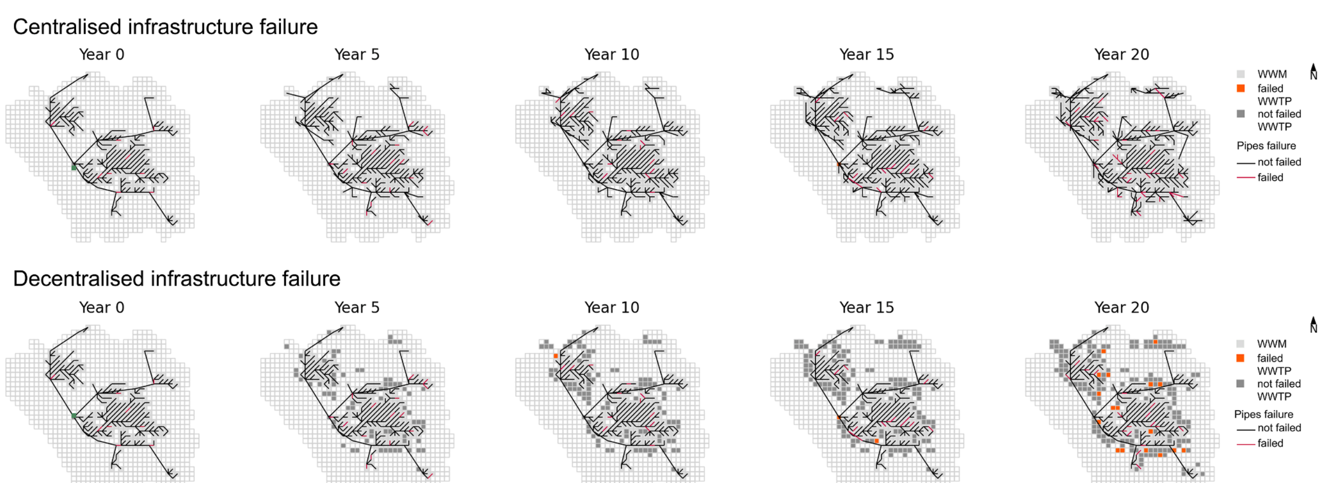

Fig. 6. Wastewater infrastructure deterioration for the centralised (top) and decentralised (bottom) alternatives in the catchment area.

small-scale WWTPs, contribute to the desirability of decentralised systems.

These results emphasise the potential of transition pathways toward decentralisation in urban water infrastructure to achieve enhanced efficiency, sustainability, and resilience in the face of evolving urban needs and challenges. To our knowledge, this is the first indication that adding decentralised elements into a fully centralised system is not only feasible, but even beneficial.

We used an exploratory approach based on a systematic system analysis to achieve this result. In large-scale models with many uncertain variables and non-linear interactions, exhaustive global sensitivity analysis can become challenging. The spatial and temporal discretisation of parameters involves substantial computational efforts (Dimov and Georgieva 2013; Şalap-Ayça et al., 2018). Also, sensitivity analysis would serve the purpose of apportioning the uncertainties in the input parameters to the uncertainty of the outputs (performance indicators). In this case, however, we are less interested in the degree to which (uncertainty of) certain parameters influence output uncertainty. Instead, we would like to understand conditions (parameter combinations) under which one management paradigm is likely to outperform

Table 3
Structural vulnerability of the network under the different cases. Empty values imply that the structural vulnerability is not affected by the corresponding cases. Highlighted values emphasise cases where decentralised systems can outperform the centralised paradigm.

CASES	Comments	Decentralised	Centralised
Baseline (with stochastic failure WWTP)	$r = 0.02\ a^{-1}$ $lifespan_p$ = 80 $lifespan_w$ = 20	0.52	0.52
A: Replacement 80%		0.52	0.52
B: Abs diff CAPEX	$a^D_{WWTP}/3$ 2 b^D_{WWTP}		
C: Abs diff OPEX	3 $OPEX_p$ $a^D_{WWTP}/5$		
D: Discount rate + CAPEX	$r = 0.03\ a^{-1}$ $a^D_{WWTP}/3$ 2 b^D_{WWTP}		
E: Ratio lifespan WWTP/pipe	$lifespan_p$ = 50 $lifespan_w$ = 50	0.69	0.664
F: Population in new areas x3		0.487	1.184

Table 4
Hydraulic capacity of the network under the different cases. Empty values imply that the hydraulic capacity is not affected by the corresponding cases. Highlighted values emphasise cases where decentralised systems can outperform the centralised paradigm.

CASES	Comments	Decentralised	Centralised
Baseline (with stochastic failure WWTP)	$r = 0.02\ a^{-1}$ $lifespan_p$ = 80 $lifespan_w$ = 20	0.855	0.898
A: Replacement 80%		0.858	0.90
B: Abs diff CAPEX	$a^D_{WWTP}/3$ 2 b^D_{WWTP}		
C: Abs diff OPEX	3 $OPEX_p$ $a^D_{WWTP}/5$		
D: Discount rate + CAPEX	$r = 0.03\ a^{-1}$ $a^D_{WWTP}/3$ 2 b^D_{WWTP}		
E: Ratio lifespan WWTP/pipe	$lifespan_p$ = 50 $lifespan_w$ = 50	0.855	0.899
F: Population in new areas x3		0.850	0.907

another on the performance indicators of interest. Qualitative system exploration methods from system analysis can reduce the computational burden of a global sensitivity analysis. In particular, system diagramming (Enserink et al., 2022) helps to identify critical factors that affect the dominance of one management strategy over another in the modelled system.

A common difficulty in system diagramming is that the distinction between the different types of factors (variables) depends on the definition of the system boundary. This, in turn, depends on the perspective of the intended beneficiary of the analysis. Different actors have varying system boundaries and problem perceptions given their societal role, resources, interests, and actions through which they can influence the behaviour of the complex, multi-actor system they are part of. For example, to a municipal wastewater infrastructure manager, the legal requirements for infrastructure performance and design guidelines can be considered external factors to their system of influence. For policymakers, changing legislation and regulation regarding infrastructure performance or design are possible actions to achieve their policy aims. Hence, they can be considered a 'means' rather than a context / external

Table 5
NPV regarding the investment costs for the different cases. Highlighted values emphasise cases where decentralised systems can outperform the centralised paradigm. The sewer infrastructure within a block is assumed to be identical for centralised and decentralised cases and therefore not considered.

CASES	Comments	Decentralised [10^6 US$]	Centralised [10^6 US$]	Diff. [10^6 US$]
Baseline (with stochastic failure WWTP)	$r = 0.02\ a^{-1}$ $lifespan_p$ = 80 $lifespan_w$ = 20	$97.3	$89.4	$7.9
A: Replacement 80%		$103.1	$94.7	$8.4
B: Abs diff CAPEX	$a^D_{WWTP}/3$ 2 b^D_{WWTP}	$86.4	$89.4	-$3.0
C: Abs diff OPEX	3 $OPEX_p$ $a^D_{WWTP}/5$	$97.1	$91.8	$5.3
D: Discount rate + CAPEX	$r = 0.03\ a^{-1}$ $a^D_{WWTP}/3$ 2 b^D_{WWTP}	$89.1	$93.9	-$4.8
E: Ratio lifespan WWTP/pipe	$lifespan_p$ = 50 $lifespan_w$ = 50	$82.1	$81.5	$0.6
F: Population in new areas x3		$148.6	$114.9	$33.1

factor. In this study, we have defined the system boundaries in line with the aim of the study.

This analysis explores different cases by varying context variables, management strategies, and parameterisations to identify conditions under which hybridisation could dominate centralised expansion on the performance indicators. The cases were built after identifying parameters that may improve the performance of decentralised wastewater systems regarding the structural vulnerability, the network's hydraulic capacity and the net present value of the costs.

Regarding the structural vulnerability index of the network under different cases, the results show that centralised and decentralised systems have similar vulnerability values, with slight variations observed when pipes are replaced by capacity. However, the decentralisation approach becomes slightly more beneficial when there is higher population density in the newly developed areas compared to the city centre. This case (Case F) demonstrates the highest difference in structural vulnerability between the centralisation and decentralisation approaches.

The results for the network's hydraulic capacity indicate that most of the sanitary sewer operates with overcapacity in all cases due to the design criteria. The decentralisation approach avoids building even more sewer capacity. It, therefore, helps to "fill" the network by increasing the flow in the system, allowing for better utilisation of the piped system. This finding suggests that decentralisation can improve the overall efficiency of the sewer network and avoid sedimentation issues.

The cost analysis represents mainly the capital costs for each case. Case B, which significantly reduces capital expenditure (CAPEX) costs for wastewater treatment plants (WWTPs), demonstrates the economic advantage of decentralised systems in the presented case study. This advantage becomes more pronounced at higher discount rates. Therefore, in locations where higher discount rates – e.g. influenced by inflation, the opportunity cost of implementing decentralised technologies, and risk considerations - the economic benefits of implementing decentralised WWTPs would be even more significant.

Further research is required to explore more extreme changes to the system's context factors and management strategies, as well as more combinations of them. This broader exploration would provide a more comprehensive view of the 'decision space' under which decentralisation is a more desirable approach. Moreover, conducting additional case studies considering different decision maker's system boundary perceptions, performance indicators, urban dynamics (i.e., land use changes, population distribution in the urban space, etc.) and population developments (growth in mega-cities or de-growth) scenarios would contribute to a more robust conclusion regarding the hybridisation of existing centralised systems.

5. Conclusions

We explored the dynamics of centralised and decentralised wastewater infrastructure across diverse case scenarios and, for each case, we introduced fresh insights into the performance of the system regarding structural vulnerability, hydraulic capacity, and net present value. This study aimed at determining the conditions favouring infrastructure hybridisation over traditional centralised paradigms. By combining system analysis with the novel *TURN-Sewers* model, we mapped the modelling problem and explore the transition space systematically. Employing system diagramming, we identified parameters influencing the assessed performance indicators. This enabled the creation of relevant simulation scenarios that reveal instances where decentralised sewer systems outperform centralised ones.

The results demonstrate for a realistic case that decentralised elements can be beneficial or similar even for realistic planning horizons. This indicates that hybrid wastewater systems are viable options for transitioning existing infrastructures into a more sustainable future. It must be emphasised that the analysis presented does not consider any additional benefits, such as nutrient or water recycling.

The findings in the current case study suggest that decentralisation can offer advantages over the centralised paradigm, particularly concerning structural vulnerability, hydraulic capacity, and investment costs. These benefits increase with higher population densities in urban expansion areas and with significant cost differences between large- and small-scale wastewater treatment plants (WWTPs). Especially, cost reductions for small-scale WWTPs can lead to substantial changes in the cost structure. These cost reductions can be possible in the future due to economies of scale and a 'learning effect' when more of these technologies are produced, as shown by (Mayor 2020) for desalination plants. The findings of this study present the potential of evaluating different transition pathways towards decentralisation in urban water infrastructures and the value of models that allow the exploration of this transition space.

Without this significant cost reduction in small-scale WWTPs and even when population density increases uniformly across existing urban areas, centralised approaches remain worth maintaining from a technical and economic point of view. The current system analysis does not consider all the possible parameter combinations and lacks validation in other case studies with different boundary conditions and urban dynamics. Therefore, further research is required to investigate the validity of these findings in different contexts and explore a broader range of scenarios.

Overall, the proposed combination of engineering modelling (using the TURN-Sewers model) and system diagramming (to identify several meaningful cases to explore) provided a valuable approach for analysing, planning, and decision-support in sanitary wastewater systems, promoting more informed and effective strategies for urban water management.

The *TURN-Sewers* model provides modular functionality for depicting the main cause-effect relationships within the system. This enables the generation of either centralised or decentralised sewer systems tailored to the urban characteristics and wastewater production in the catchment area. The model integrates assumptions and realistic scenarios to compare the evolution of sewer networks under various management strategies.

On the other hand, system diagramming provides an overview of the problem situation and helps describe the system being analysed through the model. It includes components such as system boundary conditions, criteria, external factors, means, internal factors, and causal relations. Building a system diagram allows the relationships between relevant factors to be visualised and understood, particularly the effects of means and external factors on internal factors, which ultimately impact the criteria.

When combining these approaches, system analysis can be performed to gain insights into the performance indicators of interest, such as comparing centralised and decentralised sewer infrastructure expansion paradigms.

These results highlight the potential of transition pathways toward decentralisation in urban water infrastructure, aiming to achieve improved efficiency, sustainability, and resilience to address evolving urban needs and challenges.

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CRediT authorship contribution statement

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

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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Appendix

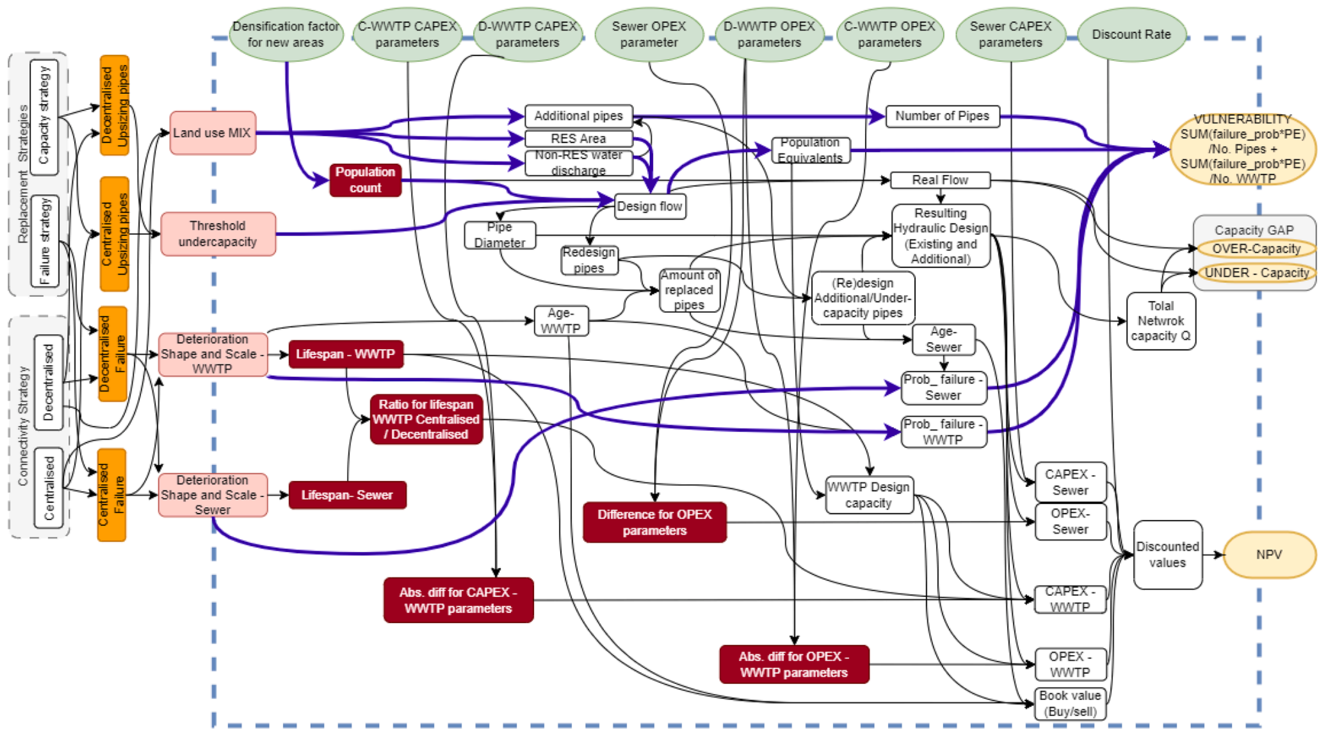

Fig. A.1. System diagram for the structural vulnerability index.

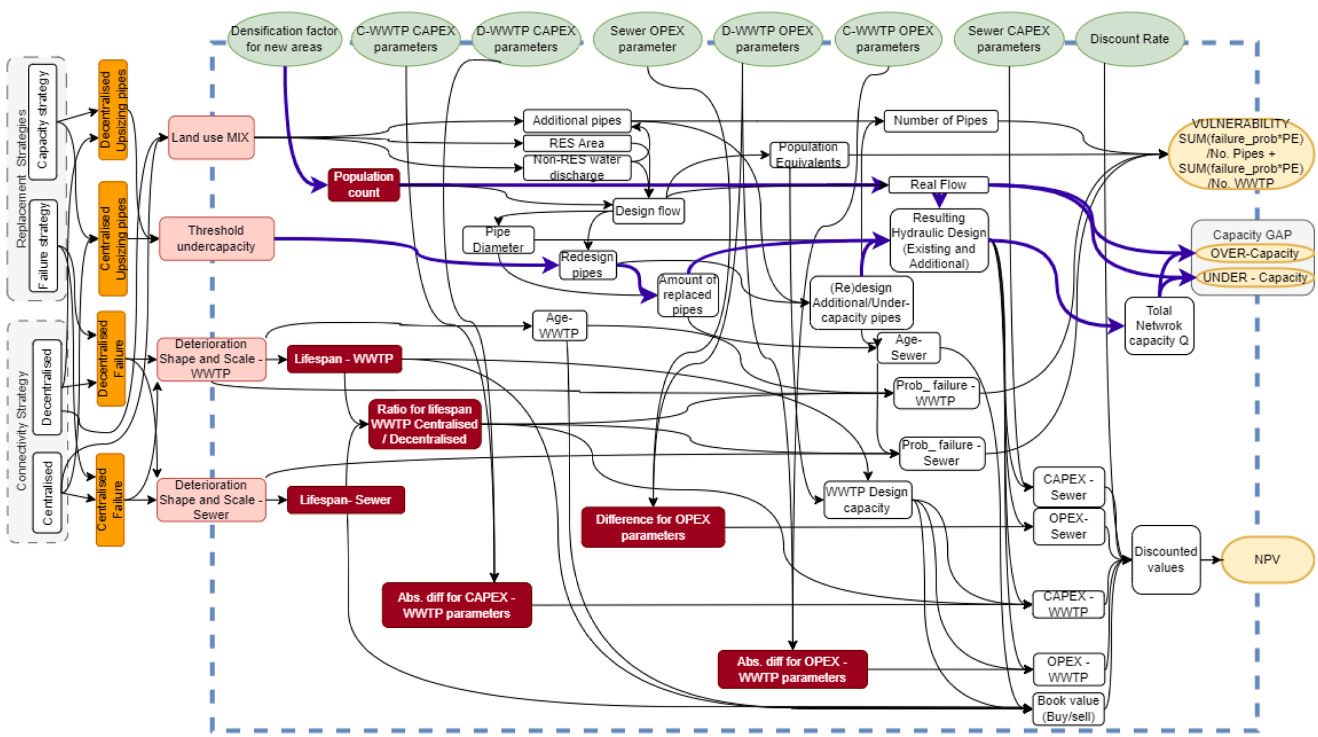

Fig. A.2. System diagram for the network's hydraulic capacity index.

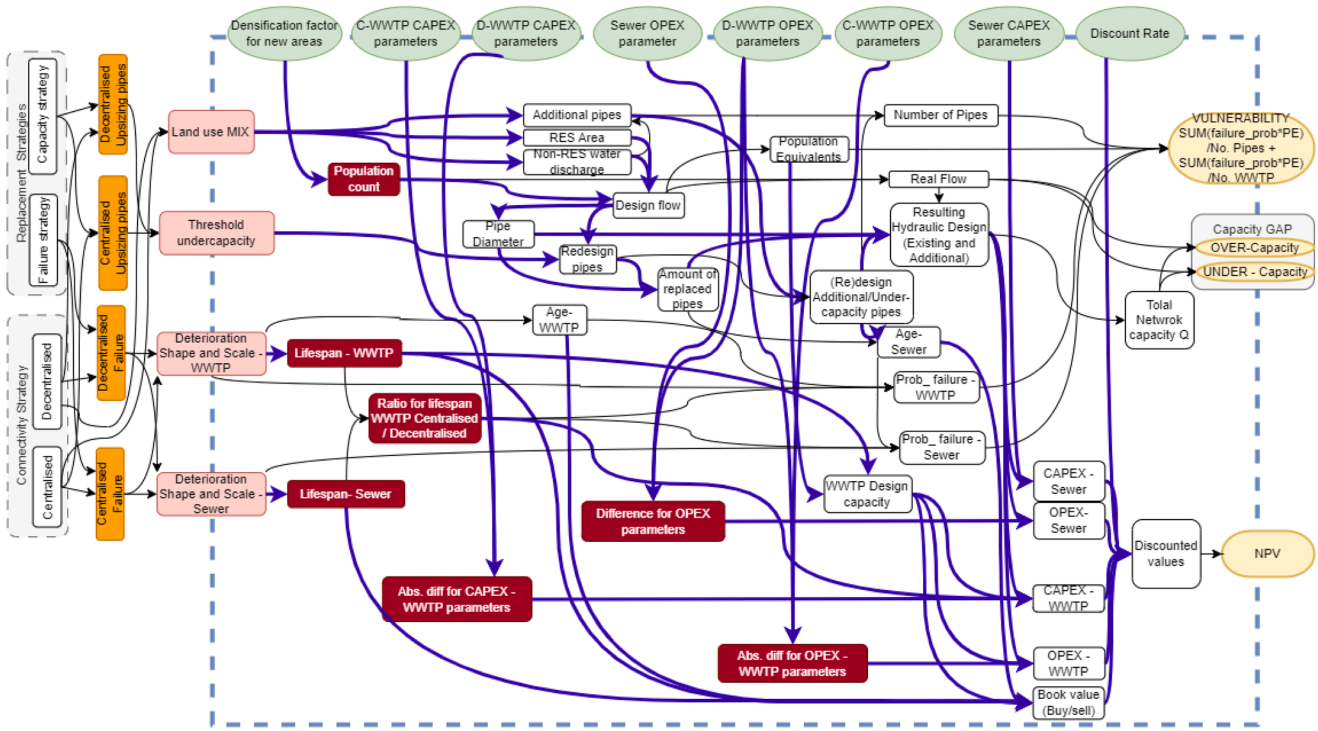

Fig. A.3. System diagram for the costs net present value.

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