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Automated screening of control potential with spatially explicit results to support dialogue about sewer overflow reduction and beyond

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ABSTRACT

For real-time control to become a standard measure for upgrading urban drainage systems, control potential screenings need to be easily integrated into the early planning processes that already take place. However, current screening methods are either not aligned with the present planning process, unrelatable for water managers or too time-consuming. We therefore developed an automated screening methodology through a co-design process with six Danish utilities. The process started out from a literature review, included interviews and workshops, and resulted in the control potential screening tool COPOTO. In the co-design process, utilities generally responded that indicators based solely on an assessment of static system attributes are insufficient. Thus, COPOTO instead post-processes the results of urban drainage simulation models that are commonly available. The decision context considered in initial planning phases was found to include environmental, economic, social and technical objectives that were highly case-dependent. When presenting CSO reduction potentials, the utilities therefore generally preferred interactive, spatially explicit visualisations that link the CSO reduction at a particular location to the storages and actuators that need to be activated. This enables water managers to discuss, for example, operational constraints of a considered control location. COPOTO provides such assessments with very limited manual and computational effort and thus facilitates the integration of real-time control into standard planning workflows of utilities.

1. Introduction

Combined sewer systems carry both wastewater and rainwater. Due to limited system capacity, these may during heavy rain discharge untreated water to rivers, lakes, and marine waters through combined sewer overflow (CSO) structures. However, there may be times where CSO occurs in one location even though unused storage capacity exists elsewhere in the system due to spatial and temporal differences in rainfall, runoff, and dry weather flow generation, as well as the inhomogeneous distribution of sewer system capacity. Real-time control (RTC) can be used to better utilise the entire system capacity and hence reduce overflows (Schütze et al., 2004a; García et al., 2015; Lund et al., 2018; van der Werf et al., 2022).

Many cities have implemented local control schemes, for example, start/stop levels for pumps (Lund et al., 2018). Real-time control can also be used to “globally” balance capacity exceedances and unused storage in different parts of the drainage network in a cost-efficient manner. However, such implementations are much less frequent. While this may partly be caused by legal and technical constraints (Beeneken et al., 2013), another issue may be how RTC is integrated into the planning process of utilities. The currently suggested approach is to perform an initial screening of control suitability, followed by a preliminary analysis including model-based testing of control algorithms, and finally to proceed into a detailed control planning stage (Schütze et al., 2008). Thus, it is assumed that utilities perform a dedicated planning process for RTC, which is however – to our knowledge – rarely the case. In addition, a tangible evaluation of control potential is not available until a preliminary control scheme has been developed in the modelling testing stage. Thus, substantial dedication and expertise is needed in the utility. This triggers the question of how we can facilitate an assessment of the RTC potential (from now on denoted ‘screening’) that is easily integrated into early planning processes that take place anyway, and that can reliably indicate whether further efforts are worthwhile. This question is the topic of this paper.

Considering the existing options for assessing control potential, these can roughly be divided into three groups. Firstly, several tools (Schütze

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et al., 2004b; Zacharof et al., 2004) perform initial assessments based on so-called static system indicators (first step in the planning process outlined by (Schütze et al., 2008)). The indicators include, for example, storage volume, distance between basins, and number of CSO structures. These assessments are fast, but they do not provide any information on what the effect of a concrete measure will be. Recent studies (Kroll et al., 2018b; van der Werf et al., 2022) further highlight that these tools do not always reflect the actual control potential.

Secondly, control potential can be assessed by implementing control algorithms in a distributed, hydrodynamic urban drainage model (see, for example, (van Daal et al., 2017; Meneses et al., 2018)). This approach has the advantage that it directly builds on models that are frequently available in the utilities. However, it requires that a control algorithm has already been designed, which makes it less appropriate for the screening phase. “Pre-configured” control schemes such as ‘equal filling degree’ (Kroll et al., 2018b) and ADESBA (Alex et al., 2008), reduce the time used for development of the control strategy. However – as highlighted in (Schütze and Haas, 2010) – this first requires a detailed initial analysis of which overflow locations to target, which storages structures to utilise, and which actuators to control, which is rather computationally infeasible in hydrodynamic models – especially if varying layouts of the pipe network should be considered during the planning phase.

Thirdly, control potential can be assessed by using lumped, conceptual urban drainage models, which reduce simulation times to a level that is acceptable in a screening situation. A traditional approach is the central basin method (Einfalt and Semke, 1994) which, however, disregards spatial rainfall heterogeneities and flow dynamics between the storage volumes and overflows. Conceptual models can also be set up in a spatially distributed manner (Langeveld et al., 2013; Löwe et al., 2016; van Daal et al., 2017; van der Werf et al., 2021) and they can then also be used in combination with “pre-configured” control schemes. However, the setup of these models then becomes a challenge for which only semi-automated tools exist (Kroll et al., 2017). This results in a new barrier in the screening process because it requires the involvement of experts that usually need to be hired from consultants or universities.

In this paper, we suggest a different approach, with the aim of enabling the integration of an initial screening of control potential directly into the design of drainage measures. We recognize that long-term simulations of rain series in distributed urban drainage models are widely performed in all planning stages. We suggest that post-processing the output from such a simulation is sufficient to provide a first estimate of the control potential that accounts for the actual dynamics in the drainage network. The screening can thus be conducted without spending time on setting up conceptual models and control algorithms or running multiple simulations. Furthermore, existing literature provides little evidence in terms of how control potentials should be presented to the utilities to enable them to decide whether control is worthwhile to pursue further. To understand how the control potential can be integrated into the utilities’ existing workflows, we conduct our development in a co-design process with six Danish utilities.

The resulting contributions of our work are:

1. A novel, fast and automated screening method to assess real-time control in initial planning stages alongside any other design option. The method is based on the assets described in a distributed urban drainage model, a single model simulation using rainfall data as input, and an automated post-processing of model results. We name the resulting tool COPOTO (control potential tool).
2. New approaches to visualise CSO reduction potentials for water managers in interactive GIS maps. These maps, for example, show which storages to control in order to obtain the largest environmental impact, and they enable end-user dialogue about other drivers and barriers to control that the utility considers important in the initial planning phase.
3. Considering six case areas, we demonstrate how COPOTO can be used to quantify the potential of RTC in varying geographical and organizational contexts.

2. Methods and case studies

The study is centred around a stakeholder process (Section 2.1), which through co-design has led to the development of COPOTO (Section 2.2).

2.1. Stakeholder process

Fig. 1a shows the steps of the stakeholder process, which aimed to shed light on three questions:

1. *Which indicators (i.e. “measures”) for CSO reduction are useful for utilities?*
2. *What is the general decision-making context (beyond CSO reduction) that utilities consider when deciding to implement real-time control?*
3. *Considering the previous two insights, how can the potential for reducing CSO by real-time control be expressed and visualised, so that it enables stakeholders to consider additional relevant decision-making criteria?*

The process was informed through a literature review, semi-structured interviews with stakeholders from each of the utilities including parallel initial interviews (see Supplementary Information A.1) and subsequent evaluation interviews focusing on the results from one utility at the time, as well as three workshops with representatives from all utilities (see Supplementary Information A.2-A.4).

The process took place over a period of 14 months (Fig. 1b). Both interviews and workshops included staff from the utilities’ planning and operational teams as well as managers. The individual attendees, however, varied from workshop to workshop. Seen over the entire project period, the division between managers, planners and operators was approximately 10 %, 60 % and 30 %, respectively.

The next three sections explain how the three questions above were addressed in the process.

2.1.1. CSO indicators

The overall scope of the paper is CSO reduction. Thus, we aimed to identify indicators for control performance that are relevant in this context. This was done in two steps, as shown in Fig. 1a (question 1).

We first elicited an initial list of CSO indicators, which was informed by a literature review using the search phrase: (“urban drainage” OR “sewer system”) AND (“potential” OR “screening”) AND (“real-time control” OR “RTC”). We screened all references and identified those that included information about CSO indicators. We furthermore consulted the references in the selected literature, and also used Scopus to find literature that cited some of the key references. CSO indicators were also elicited from the participating utilities in workshop 1 by asking the participants *“How do you calculate and visualise the control potential – and should it be shown in different ways to different people (operational team, planning team, leadership)?”*.

The initial list of CSO indicators was reduced to a shorter list based on discussions in the project team. The shortlist contained only indicators that could be quantified given the utilities’ asset database and the urban drainage simulation results, since one of the premises of this work was to take advantage of the urban drainage models that today are available in many utilities. The full list of indicators and the motivation for selecting the shortlisted indicators is documented in Supplementary Information B.

2.1.2. General decision-making context

We mapped drivers for and barriers to control in order to identify the objectives that guide the decision-making process of utilities besides CSO reduction (Fig. 1a, question 2).

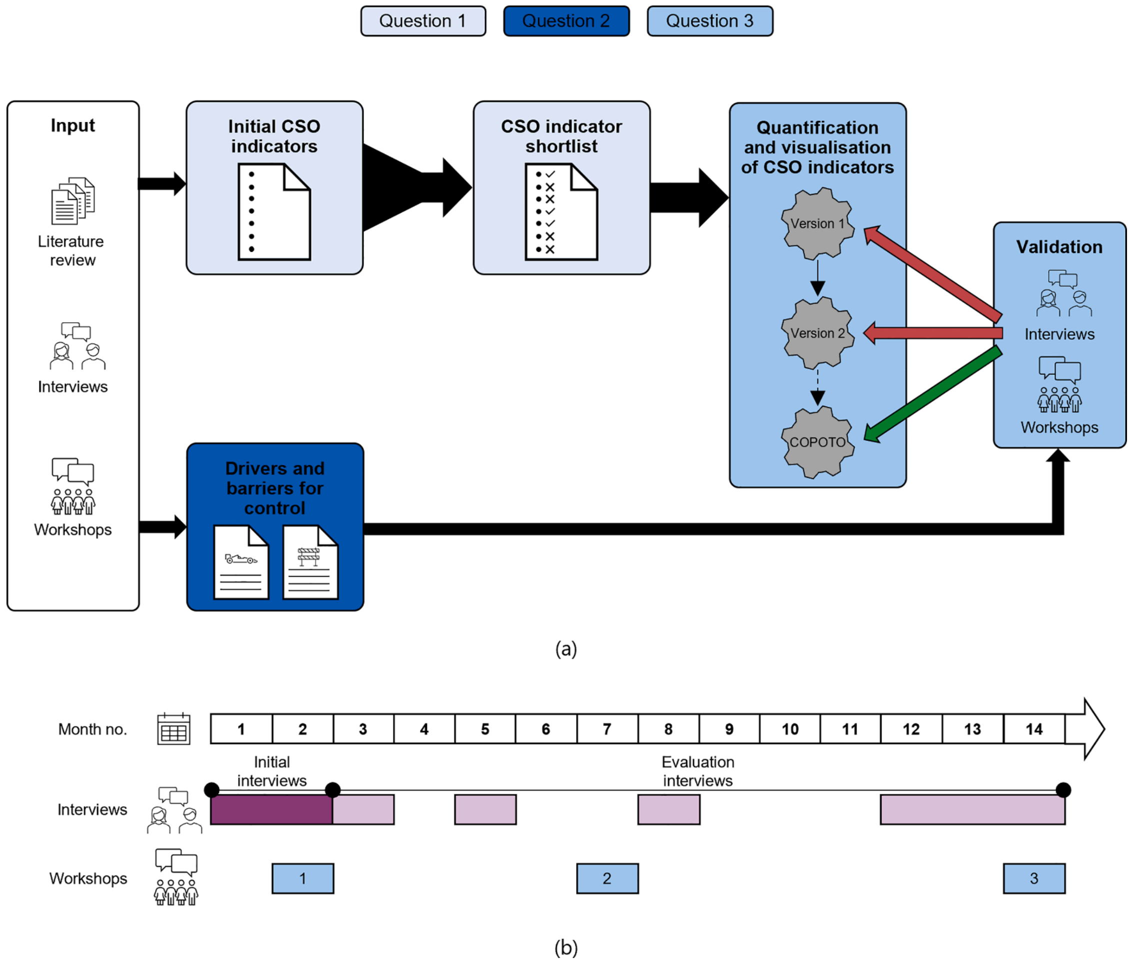


Fig. 1. Stakeholder process. (a) Methodology overview; (b) Project time frame.

This was done through the literature review described earlier, but this time selecting references that included information about drivers and barriers. Furthermore, the utilities contributed to the elicitation in both interviews and workshops through prepared questions and unstructured discussions. The utilities were asked:

- *"Why is control relevant compared to other solutions?"* (initial interviews)
- *"Why does the utility not use control more than it does today, what are the barriers?"* (initial interviews)
- *"List the situations where control can be helpful – and which 'dangers' there could be in each of these situations (what is the control not allowed to do)?"* (workshop 1)
- *"Which drivers and barriers are there to control"* (workshop 2)

Some identified objectives were listed as both drivers and barriers since their perception by water managers depends on, for example, the already existing equipment in the specific system and the culture and organisational structure of the utility.

If objectives had different names but equivalent meaning, they were merged in an initial coding step. In the next step, we created groups of objectives that are related to the same overall decision context. Finally, in the same way as Lienert et al. (2015) and Skrydstrup et al. (2020), all objectives were categorised considering the three pillars of sustainability (environmental, economic, and social objectives), as well as a technical category. The coding process is detailed in Supplementary Information B.

2.1.3. CSO indicator visualisations

We wanted COPOTO to include a selection of the shortlisted CSO indicators, which can be expressed and visualised in ways that are meaningful for the broader decision-making process. The selection was done through an iterative approach with staff from the participating utilities, as shown in Fig. 1a (question 3).

Different visualisations of the shortlisted CSO indicators were therefore developed and evaluated. This was done based on how the control potential was presented in literature and from the vague responses when asking the utilities *"How do you calculate and visualise the control potential – and should it be shown in different ways to different people (operational team, planning team, leadership)"* in workshop 1.

The assessment of the CSO indicator visualisations was twofold: 1) does the indicator and its visualisation provide information that the utilities find valuable in terms of CSO reduction?; and 2) does the indicator and its visualisation enable the utility to address other decision-making variables? In order to assess this, the developed visualisations were shown at the evaluation interviews with the first utility and – depending on the response – either discarded or shown in original or altered form at workshop 2 for plenum assessment. The indicator visualisations were then altered and expanded in the subsequent evaluation interviews with the remaining utilities. The final version of COPOTO was validated in workshop 3 by asking the participants *"Analyse your catchment(s): Find examples where it would be easy to implement control and examples where it would be difficult"*.

2.2. COPOTO: control potential screening tool

2.2.1. Overall concept of COPOTO

Many CSO indicators were quantified and visualised during the co-design process with the utilities, and the process suggested that it is crucial to identify how much the CSO volume and frequency can be reduced at each CSO location, and which storages and actuators need to be activated for this purpose. This thus constitutes the finally selected subset of CSO indicators. The aim was to derive a methodology that quantifies these indicators using existing urban drainage models, while enabling a qualified estimate with very limited manual effort and computation time. The computation of control potential therefore relies on a single hydraulic model simulation of a (user-selected, and preferably long and spatially distributed) rain series, and the subsequent automatic post-processing of model results. This section describes how COPOTO quantifies control potential.

Fig. 2 illustrates the workflow of COPOTO. The left side outlines the overall workflow, and the right side shows how the algorithm of COPOTO works and the required user inputs.

COPOTO calculates the control potential (Fig. 2, right) by subdividing the time series of simulation results into events. An event is defined as the time period from when runoff starts entering the system and until the flow or water level at the WWTP returns to near-dry weather flow conditions. COPOTO then performs a volume balance calculation for each event where CSO volume is “distributed” across storage structures with unused capacity. As detailed in Section 2.2.2, this calculation accounts for the network structure of the drainage system as well as the unused storage volume, flows, transport time, and backwater in the system. The calculation proceeds one CSO location at a time. The order in which CSO locations are processed is a user input, which, for example, allows overflow from the most critical location to be reduced first. The overflow volume is distributed first to storage structures upstream from the CSO location and – if there is still overflow volume left – to storage downstream of the CSO location, because upstream storage is generally easier to control. To minimise the number of storage structures that need to be controlled, the algorithm examines the structures in order of decreasing unused storage volume in the given event.

The algorithm thus evaluates how much CSO can be reduced at each individual CSO point during each individual event. Alongside the location where CSO is reduced, we record which actuator should be controlled to reduce the CSO, and which storage structure should be used for storing the overflow volume. In this way, we create a relation between CSO locations, actuators, and storage structures. The results are aggregated into a total number of CSO events and volume of CSO that can be reduced at each CSO location by activating a specific actuator and storage. This not only enables a concrete discussion on the potential CSO reduction at specific locations, but the spatial visualisation later enables discussions of other environmental, social, technical, and economic planning objectives.

2.2.2. Computing CSO reduction potential at a specific CSO location, by activating a specific, controlled storage volume during a specific event

As described in the previous section, COPOTO performs a volume balance calculation to assess how much of the CSO volume occurring at a specific location during a specific rain event can likely be avoided by controlling a specific storage structure.

Storage structures that should be considered in the analysis are selected by the user. This can include both basins as well as in-line sewer storages. In general, storage structures are only considered if their

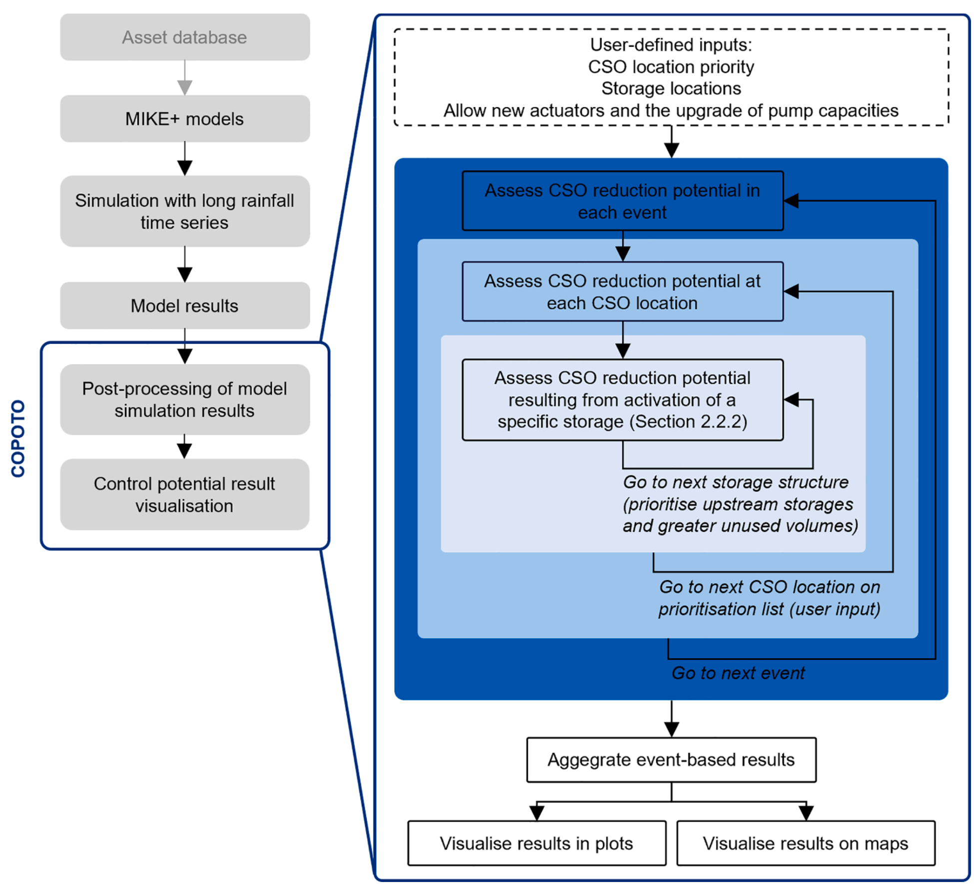


Fig. 2. Flowchart of control potential calculation. The left side outlines the overall workflow. The applied MIKE+ models build upon the utilities’ asset databases, but since we did not perform the database-to-model conversion in this study, the asset database is marked with grey text. The right side shows the algorithm implemented in COPOTO.

outflow is controlled by an actuator. If the storage is off-line, the inflow must also be controllable. If an actuator does not exist, then the user can allow the algorithm to insert a new one. In practice, the algorithm does this by assuming it can control the flow through a presently uncontrolled pipe or weir. Likewise, the algorithm may upgrade the pump capacity of existing pumps with a user-defined factor. The algorithm never increases maximum outflows from the storage structures to avoid issues with pipe capacities and increased CSO downstream.

CSO can be reduced by using storage structures that either discharge water towards the CSO location (storages upstream the CSO location) or receive water from the CSO location (storages downstream the CSO location). If no unused volume is available in the downstream storage structure, COPOTO tries to increase the available volume by using storages in other branches upstream of this. The potential for reducing CSO volume (ΔCSO) using a specific storage structure is computed as the minimum of three values (Eq. (1)): 1) the total CSO volume occurring at the location in question minus any reductions from storage locations that have been considered before the storage location in question (V_{CSO}), 2) the unused storage volume in the considered storage structure ($V_{storage,unused}$), and 3) the water volume that can either be prevented from flowing out of the storage structure, or be directed into the storage structure in the period where the CSO in question occurs (V_{flow}).

$$\Delta CSO = \min(V_{CSO}, V_{storage,free}, V_{flow})$$

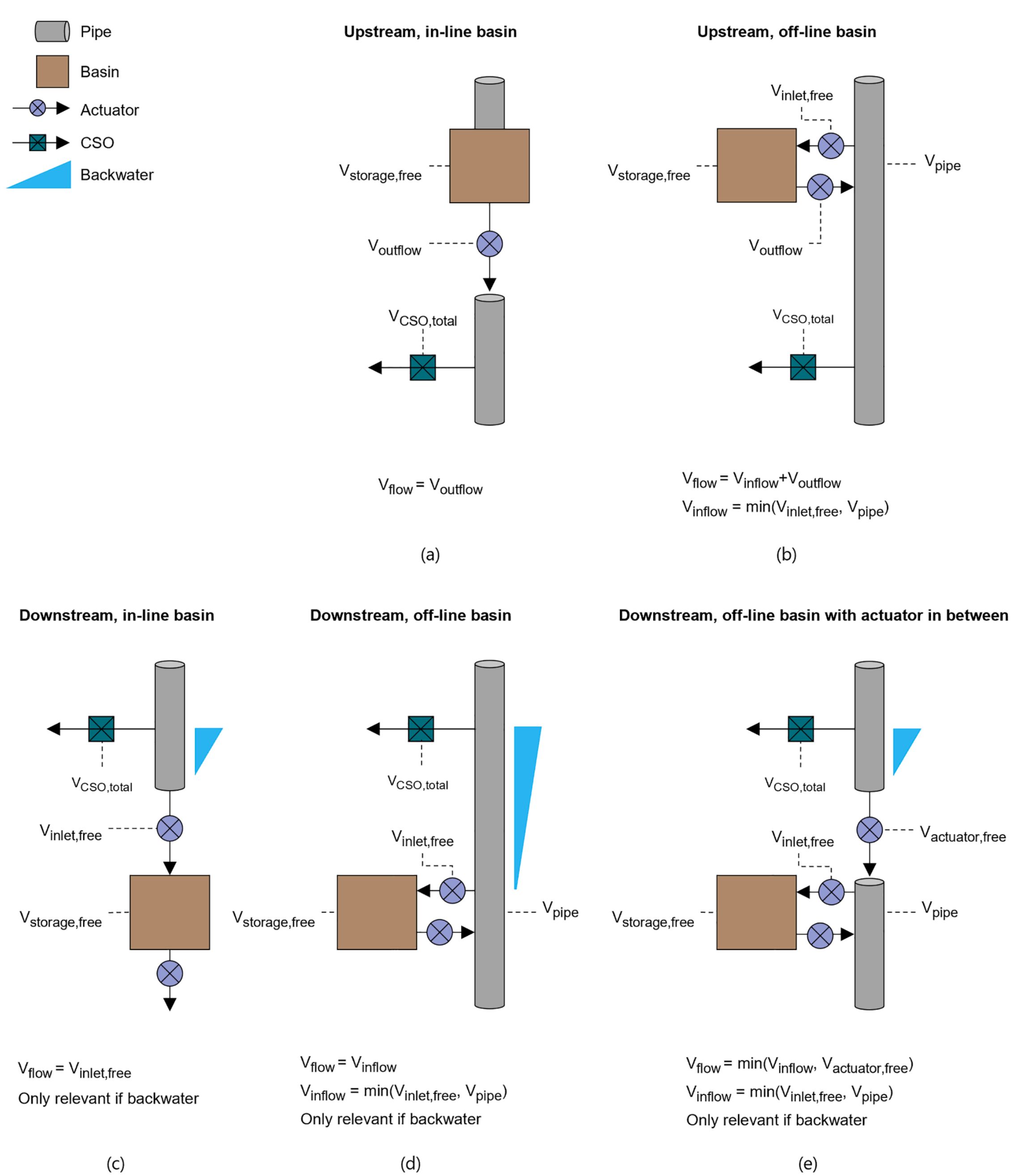


Fig. 3. Sewer system constellations that are managed differently in COPOTO. (a) In-line storage upstream of CSO location; (b) off-line storage upstream of CSO location; (c) in-line storage downstream of CSO location; (d) off-line storage downstream of CSO location; (e) off-line storage downstream of CSO location with actuator in between. $V_{CSO,total}$ = total CSO volume; $V_{storage,unused}$ = unused volume in storage; $V_{outflow}$ = storage outflow volume; $V_{inlet,unused}$ = water volume that can be directed into the storage without exceeding the flow capacity of the inlet; V_{pipe} = passing water volume in pipe that can potentially be redirected into the storage; $V_{actuator,unused}$ = water volume corresponding to the unused flow capacity through the actuator.

$$\Delta CSO = \min(V_{CSO}, V_{storage,unused}, V_{flow}) \tag{1}$$

In the following, we detail how V_{CSO}, $V_{storage,unused}$ and V_{flow} are assessed.

CSO volume (V_{CSO}) that can be reduced by the considered storage structure

The total CSO volume for a CSO location ($V_{CSO,total}$) is calculated by integrating the CSO flow over time for the event in question. COPOTO sequentially distributes the CSO volume from a particular location across multiple storage structures. When considering the j^{th} storage structure, the remaining reducible CSO volume $V_{CSO,j}$ therefore corresponds to the total CSO volume at the considered CSO location in the considered event ($V_{CSO,total}$) minus the sum of the CSO reductions (ΔCSO_i) that have already been assigned to the i = 1, …, (j-1)th previously considered storage structures.

Unused volume in the considered storage structure ($V_{storage,unused}$)

The unused volume of a storage ($V_{storage,unused}$) that can be used to reduce CSO is calculated based on the total storage volume of a given element (V_{total}) and the maximum used storage at any time during the event ($V_{used,max}$) (Eq. (2)).

$$V_{storage,unused} = V_{total} - V_{used,max} \tag{2}$$

Using this approach, the unused storage volume is independent of the timing of the storage structure filling. It thus presents a conservative estimate of the storage volume that can be used. The total volume V_{total} for each storage is derived based on the crest level of the existing overflow weir. In this way, we limit the considered storage to the amount that was considered in the hydraulic design of the network.

Flow volumes to/from the considered CSO location (V_{flow})

When activating a specific storage structure, the CSO reduction potential is limited by the water volume that can be prevented from flowing towards the CSO location by utilizing upstream storage structures, or the water volume that can additionally be directed towards a downstream storage structure (V_{flow}). The layout of the sewer system (and thus what is upstream and downstream) is known from the definition of upstream and downstream nodes for each pipe, pump, etc. in the model. The computation of V_{flow} can handle the presence of multiple flow paths between the storage structure and CSO location. How the computation of V_{flow} is performed depends on where the storage is located relative to the CSO location (upstream/downstream), and how it is placed in the drainage network (in-line, off-line). We distinguish five different cases as illustrated in Fig. 3. If there is only one flow path between the CSO location and upstream or downstream storage structure, and this contains an internal weir, V_{flow} is additionally limited by the flow over this weir. This is however not visualised in Fig. 3.

The flow volumes (V_{flow}) are assessed differently for each of the five cases presented in Fig. 3:

a) Upstream, in-line storage structures (Fig. 3a) can at most retain the volume of water that leaves through the outlet ($V_{outflow}$) during the period where CSO occurs. Thus, we compute V_{flow} by integrating the outflow during the CSO period. Reductions of the outflow at an upstream storage do not immediately impact the flow at the actuator. Therefore, we consider a time shift that corresponds to the transport time between actuator and CSO location (see "Transport time" below).
b) Upstream, off-line storage structures (Fig. 3b) can at most retain the flow volume that can be let into the storage (V_{inflow}) and the flow that runs through the outlet ($V_{outflow}$). The amount of water that can be let into the storage structure is the minimum of the water volume passing by the structure (V_{pipe}) and how much of this can actually be directed into the storage ($V_{inlet,unused}$). The latter is quantified from the additional capacity that is present in the actuator connecting the sewer network and the structure. If the connecting element is a weir or gate, we assume an unlimited transport capacity. If the connecting element is a pump, the maximum capacity is a user input. $V_{outflow}$, V_{pipe}, and $V_{inlet,unused}$ are – as in case a) – computed by integrating the flows during the CSO duration, considering a time shift that corresponds to the transport time between actuator and CSO location.
c) Downstream, in-line storage structures (Fig. 3c) can only reduce CSO if additional volume can be transported from the CSO location to the storage structure. This is only possible if an actuator with unused flow capacity exists between the CSO location and the storage structure. Opposed to cases a) and b), we assume that we can only increase the flow towards the downstream storage structure in periods where backwater occurs (see "Backwater" below). Otherwise, an increase of the downstream flow capacity would not have an effect on the flow passing by the CSO. When backwater is present, we assume that an increase of the downstream flow capacity has an immediate effect on the flow passing by the CSO, and that water flows are not limited by any bottlenecks between the CSO and the actuator. The flow volume V_{flow} that can be directed away from the CSO is thus computed as the unused flow capacity of the actuator ($V_{inlet,unused}$) during the time period where both CSO and backwater are present.
d) Downstream, off-line storage structures (Fig. 3d) can reduce CSO by the volume of water that can be let into the storage structure. As in case b), this is the minimum of the volume passing by the structure (V_{pipe}) and the unused capacity of the actuator at the storage inlet ($V_{inlet,unused}$) during the time period where both CSO and backwater are present. Similar to c), the reducible CSO volume is 0 if there is no backwater between the inflow to the storage and the upstream CSO.
e) In the situation where an actuator exists between a downstream, off-line structure and the CSO location (Fig. 3e), we – contrarily to case d) – assess backwater between this actuator and the CSO location. The integrated, unused flow capacity of the actuator ($V_{actuator,unused}$) becomes an additional constraint for the potential CSO reduction compared to case d).

Accounting for transport time for upstream storage structures

When using upstream storage structures to decrease downstream CSO there will be a time delay between when the structure is activated and until the effect is seen at the CSO location. Therefore, we account for the transport time when calculating V_{flow} (Fig. 3a,b) by integrating the assessed flow over a time period prior to the CSO occurrence as shown in Fig. 4a.

The transport time is calculated by summing the transport time of each individual pipe between the location of the assessed flow and the CSO. The transport time in each pipe is calculated by dividing the pipe length with the maximum velocity simulated in the pipe during the event.

The transport time is not considered when investigating the usage of a downstream basin (Fig. 3c,d,e) since we assume that the effect of control on decreasing the hydraulic head at the CSO location will be instantaneous.

Accounting for backwater for downstream storage structures

If the investigated storage structure is located downstream of the CSO location (Fig. 3c,d,e) the flow volume passing by the CSO location can only be increased if backwater occurs between the CSO location and the closest downstream actuator. The closest actuator can either be located on the main path (Fig. 3c,e) or where the water enters an off-line structure (Fig. 3d).

To determine periods where backwater occurs in the hydrodynamic simulations, we need to define a criterion for when the flow conditions at the downstream actuator affect the flow passing by the CSO. This is the case when the hydraulic head at the downstream actuator is higher than the invert level at the CSO location (Fig. 4b). We note that this is a

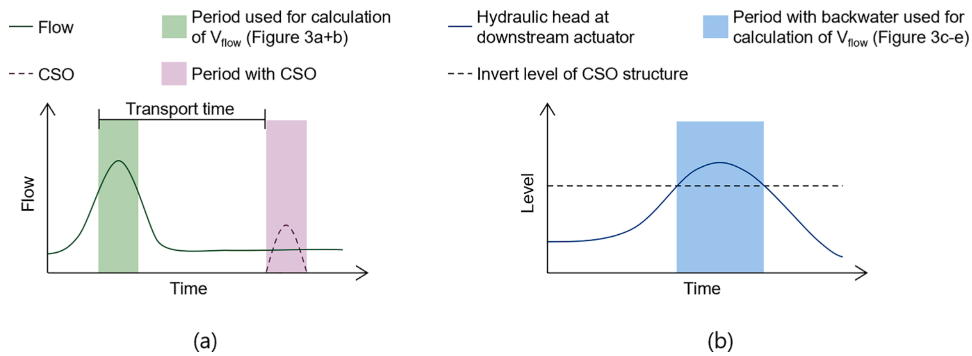


Fig. 4. Conceptualization of how transport time and backwater are taken into account. (a) The assessed flow upstream of the CSO structure is considered only during the period prior to the CSO corresponding to the transport time between the location of the assessed flow and the CSO. (b) Backwater is defined as the situation when the hydraulic head at the downstream actuator is higher than the invert level of the CSO structure. The assessed flow at the downstream actuator is considered only during the period with both backwater and CSO.

simplifying assumption, because backwater can already occur dynamically for smaller hydraulic heads downstream, while the safest assumption would be to consider only time periods where the downstream hydraulic head exceeds the weir crest of the CSO. This situation will, however, rarely occur in practice.

V_{flow} is calculated only in the period where both backwater and CSO occur.

2.2.3. *Case areas*

COPOTO was developed through a co-design process centred around cases from six participating utilities (Table 1). The cases vary in areal extent, storage volume, control experience, internal organisation, and expectation towards CSO reduction.

For each case area, we obtained a spatially distributed, hydrodynamic urban drainage model in MIKE+ (DHI 2022), which supports lumped rainfall-runoff simulation from distributed sub-catchments to the sewer system, distributed hydrodynamic simulation of the sewer system, and the simulation of different structures such as pump, weirs, and gates, as well as of control strategies. Four years of C-band radar rainfall data from the Danish Meteorological Institute (2017–2020) was used as input to the MIKE+ models. The data had a temporal resolution of 1 min and a pixel size of 500 m, and we adjusted these data with rain gauge data in each of the six case areas. The models were run only once, which for each case area took less than a day. These simulations are anyway performed when redesigning urban drainage networks in an area.

We subsequently ran COPOTO using overflow location priorities and storage locations provided by the utilities. The tool was run twice: once with the current system setup, and once where the tool was allowed to insert new actuators. In the latter case, we assumed an allowed increase of pump capacities by a factor of three, with the exception of few long transport pumps where the capacity was not changed. COPOTO can be run in a couple of hours.

3. Results

We here show results for each of the three questions from the stakeholder process (Section 2.1).

3.1. *CSO indicators*

To assess the potential of real-time control in the context of reducing CSO, 53 indicators were identified in literature, interviews and workshops. Table 2 shows the shortlist of nine indicators which can be

Table 1
Key information from the six case areas. The system information is taken from the MIKE+ model while the control information stems from the initial interviews*.

Utility	Pipes [km]	Nodes [#]	Impervious area upstream storages [ha]	Total storage volume [m^3]	Total specific storage [mm]	In-line basins [#]	Off-line basins [#]	Highest level of control in utility	Responsible department	Utility employees' initial expectation to CSO reduction
Utility 1	87.3	2116	64.5	4077	6.3	4	14	Two locations controlled based on water levels in other parts of the system (one is close by the controlled actuator and the other is further away)	Planning and operations in collaboration	20 %
Utility 2	46.9	1312	102.9	10,599	10.3	1	6	Cascade control	Planning (WWTP) and operations (WWTP) in collaboration	Unknown
Utility 3	195.1	4011	124.8	28,355	22.7	3	8	Start/stop levels of pumps	First planning, then operations	10 %
Utility 4	42.5	1131	106.2	4145	3.9	5	4	Start/stop levels of pumps	Operations (WWTP)	Not 50 %, but a lot
Utility 5	64.1	1777	66.4	2281	3.4	8	2	Start/stop levels of pumps	Single person	5 %
Utility 6	95.5	2630	35.4	755	2.1	3	1	Start/stop levels of pumps	Planning and operations in collaboration	40–50 %

* Specific storage is calculated as the storage volume divided by the impervious area.

Table 2
Shortlisted nine CSO potential indicators, their computation method, and their origin. A CSO event is defined as any spillage of water through an external weir. If two CSO events have less than 24 h between them they are considered as one CSO event.

Abbr.	Indicator	Unit	There is potential if the indicator is...	Computation of indicator	Elicited from	
					literature	utilities
S1	Number of storage structures	[#]	Large → because this means that there may be an unequal filling of the system	Extract from static system properties	x	
S2	Size of storage volume	[m^3]	Large → because this means that there is a larger volume to use for storage		x	
S3	Size and distribution of specific storage volume	[m^3/ha] or [mm]	Large and unevenly distributed, especially if there is more volume downstream → because storage structures will fill unequally if there is a combination of small and large specific storage volumes		x	
S4	Size of flow capacity of network	[m^3/s]	Large → because this means that water can be quickly removed from the CSO location		x	
S5	Number of actuators	[#]	Large → because there is a higher chance that water can be stored in a storage structure with unused capacity if there are many actuators		x	
S6	Number of CSO structures	[#]	Large → because there is a larger chance that there is at least one of these connected to a storage structure with unused capacity		x	
D1	Overflow while unused storage	[yes/no] or [filling degree]	Yes (before control) → because the unused storage could be activated to minimise CSO	Extract from dynamic simulation results	x	x
P1	Number/frequency of CSO events	[n], [n/yr] or [%]	Lowered by control	Post-processing is used to add a layer of interpretation to the dynamic simulation results	x	x
P2	CSO volume	[m^3/s], [m^3], [m^3/yr] or [%]	Lowered by control		x	x

derived from the utilities' asset databases or by running distributed urban drainage models. Six of these can be directly derived from static system attributes, while three require model simulations. The utilities themselves only suggested indicators that require model simulations, and they did not propose that different CSO indicators were needed for operators and planners. CSO pollution loads and surface water impacts were not considered because water quality models were not available for any of the participating utilities.

Initial visualisations of the control potential were subsequently based on the indicators in Table 2. The co-design process started with static system properties and progressed into more elaborate indicators (Section 3.3). The wider set of planning objectives that arise during the development of real-time control schemes (Section 3.2) were additionally considered.

3.2. *General decision-making context*

We elicited the wider decision context that utilities consider when deciding for or against real-time control. An understanding of this context is vital both to present the CSO reduction potential in a way that facilitates a simultaneous discussion of these objectives, and to identify potential further developments. Table 3 shows an overview of the coded objectives in each of the four categories. A full list and description of all drivers and barriers to control can be found in Supplementary Information B. The four categories are described in more detail below. A key insight is that the drivers and barriers for control strongly vary between cases. Screening of control potentials should therefore foster dialogue between local stakeholders, such that potential drivers and barriers can be identified in the early planning phase.

Amongst *environmental objectives*, the improvement of the ecological and chemical quality of surface waters is one of the main drivers for considering real-time control, and it is included in all of the reviewed studies. The utilities highlight that the ability to assign improvements to a specific surface water body greatly improves the usability of the assessments for planning purposes. Real-time control is by some utilities seen as an intermediate solution to improve water quality as much and quickly as possible while simultaneously carrying out, for example, sewer system separation that can take decades to finalise. The reduction of greenhouse gas emissions is a second environmental objective that was elicited both from the literature and the utilities. This entails avoiding emissions resulting from infrastructure construction (Brudler et al., 2019), reducing energy consumption (Kroll et al., 2018a), aligning energy consumption with the production of renewable energy (Stentoft et al., 2021), and optimizing treatment processes to reduce N_2O emissions (Vasilaki et al., 2019).

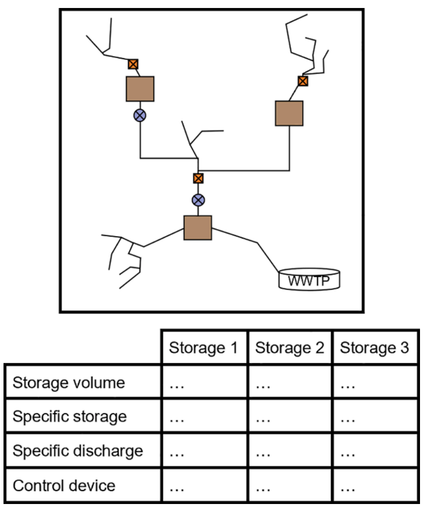
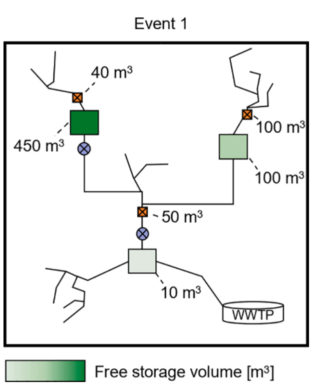
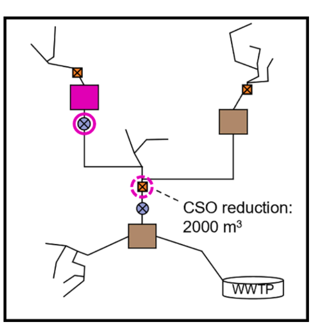
Economic objectives are also important drivers for real-time control since control is commonly considered cost-effective as compared to structural measures (highlighted in more than 50 % of the reviewed studies). However, this was not common knowledge for all the participating utility employees. Further insights from literature and the dialogue with the participants were that the size of each cost category cannot be generalised as they depend on the project, the experience of planners and operators, and the equipment already present in the urban drainage system. In addition, economic regulation of public utilities may lead to different cost components being budgeted differently. For example, in Denmark structural and operational expenses are regulated separately. Thus, the utility may have financial resources for constructing new storage structures, but not for the increased operation and maintenance that may come with control of these storage structures.

Social objectives are often presented as barriers but could serve as drivers too. Control is frequently seen as complicated and demanding, and the lack of experience with real-time control implementation and assessing control potentials are key barriers. These are amplified if employees already are pressed for time, or by the hassle of being forced into collaboration across departments. The same objectives can act as drivers when planners and operators obtain a better system

Table 3
Coded objectives for control within four overall categories.

A Environmental	B Economic	C Social	D Technical
Environmental quality of surface waters Greenhouse gas emissions	Economic regulation Flood damage Implementation cost Operation/maintenance cost Planning cost	Compliance with business strategy Control knowledge & experience Employee satisfaction External pressure Focus on citizens health Perception of hassle Required work effort	Flexibility Physical preparedness Robustness of operation Technological preparedness

Table 4
A subset of the evaluation of CSO indicators shown in Supplementary Information A.5. The indicator abbreviations (S1-S6, D1, P1-P2) refer to the names in Table 2. A: Extracted from static system properties, B: Extracted from dynamic simulation results, C: Post-processing is used to add a layer of interpretation to the dynamic simulation results. Both basins and in-line sewer storage can be used to represent storage structures in COPOTO even though only basins are used in the visualisations in this Table.

No.	Visualisation	Information
A		Description: A map showing storage structures and CSO locations, and a table with static attribute information. Indicators: Number of storage structures (S1), size of storage volume (S2), size and distribution of specific storage volume (S3), size of flow capacity of network (S4) (the specific discharge [L/s/ha] was shown), number of actuators (S5), and number of CSO structures (S6). Reasoning: The visualisation provides a spatial overview of system attributes that are typically associated with high control potential. Feedback: + Contributed to a good system overview. - Information about the number and location of storages, actuators and CSO structures do not provide insights into control potential (S1, S5, S6). - Information on storage volume and discharge cannot be interpreted without knowledge about how the system acts under dynamic loading and the spatial distribution of overflow volumes (S2, S3, S4). - It is neither possible to address CSO reduction nor other decision variables.
B		Description: A map showing unused storage volume (colours and values) together with the CSO volumes (values) for a single event. Indicators: Overflow while unused storage (D1). Reasoning: The visualisation can be used to make a manual assessment of the path between storage structures with unused capacity and CSO locations, which can give insights into which specific CSOs can be reduced. Feedback: + If there is no unused storage volume, control can be disqualified as solution. - Manual assessment of the connection between storages and CSOs is a tedious task. - Information about the pipe flow and flow capacities of actuators is lacking. - It is not possible to address other decision variables. - Each simulated event requires its own plot, and the analysis task thus quickly becomes large.
C		Description: A map showing the relation between a single CSO location (in pink, dashed circle), the upstream storage structure that should be exploited to reduce the CSO (colored pink), and the actuator that needs to be activated to obtain the reduction (in full pink circle). The amount of CSO that can be reduced (on average, per year) using this relation is shown next to the CSO structure. One such map exists per combination of storage and actuator that can reduce the CSO at a given location. Indicators: CSO volume (P2). Reasoning: The visualisation provides the relation between CSO location, storage structure and actuators, which enables a concrete and detailed conversation around many important decision variables. Feedback: + Functions as a dialogue tool. + Enables the discussion of CSO reduction as well as many other decision variables.

understanding through the implementation and operation of control schemes, enjoy a continuous dialogue between each other and with authorities, and when a change of control scheme reduces, for example, the time required for maintenance. The implementation of modern operation strategies and the development of new skills can further increase employee satisfaction. Mitigation of social barriers calls for involvement of relevant stakeholders (including operators) in the early planning phase and for the development of tools for assessing control potential that as far as possible support dialogue and assist in making control understandable, such as COPOTO.

A number of *technical objectives* furthermore determine whether real-time control is an attractive option in a particular system. Amongst physical constraints, lack of space for storage structures may, for example, be a driver for control. On the other hand, lack of unused system capacity and the fact that existing structures may not be suitable for the installation of sensors and actuators can hinder control implementations. The technological ability of managing, for example, data transfers and monitoring actuators can be a driver if the required systems are in place, or a barrier if real-time control, for example, requires replacing the existing SCADA system. Real-time control also introduces a range of vulnerabilities related to IT security or risks from maloperation of actuators which generally act as a barrier, while the flexibility of adapting control schemes in case of changes of the sewer network or new environmental regulations is a driver.

3.3. CSO indicator visualisations

We considered the shortlisted CSO indicators from Section 3.1 as a starting point for developing visualisations that illustrate the potential for reducing CSO, while keeping in mind other decision-making criteria highlighted in Section 3.2. As described in Section 2.1.3, the visualisations were successively refined through interviews and workshops with the utilities.

Following the structure of indicators in Table 2, we presented the utilities with three groups of visualisations:

- visualisations where potential indicators are directly derived from static system attributes
- visualisations where results from dynamic simulation are directly presented
- visualisations where post-processing is used to add a layer of interpretation to the dynamic simulation results

Table 1 in Supplementary Information A.5 shows an overview of the visualisations in the order they were developed, together with a description and reasoning of the visualisation as well as the utilities' feedback. A subset of this is shown in Table 4, and the following paragraphs summarize the overall feedback on the different visualisation groups from the utility participants.

The utility participants were not able to relate visualisations of static system information (exemplified in Table 4, row A) to potential CSO reduction. This was mainly due to missing information about the dynamic system response, and these visualisations were hence disregarded.

Some of the visualisations showing information extracted from dynamic simulation results required an individual plot per simulation event (exemplified in Table 4, row B). This amount of information can quickly become overwhelming when the model results span many events. Average values cannot be used since, for example, a storage structure with an average low filling degree may always be filled when there is overflow from nearby CSO locations. Furthermore, the utility participants found that the visualisations were missing information about the connection between system elements and about flows and capacities. The utility participants could thus also not use these visualisations in their decision process.

Post-processing the model results in COPOTO enables the visualisation of potential reductions in CSO volume and number, and generates maps that contain the CSO volume reduction at a single location together with the storage structures and actuators that need to be activated to obtain this reduction (exemplified in Table 4, row C). The utility participants found that this visualisation worked well as a dialogue tool, which is elaborated further in Section 4.1. Standardised plots and maps form a good basis for discussion, but additional customised visualisations that serve local needs will likely be needed.

4. Discussion

4.1. How screening of control potentials improves the planning process

4.1.1. Why spatially explicit visualisations of control potential support dialogue

As documented in Section 3.2, utilities consider a broad range of indicators when evaluating whether real-time control is feasible for their catchment. These vary from city to city (also supported by (Mollerup et al. 2013)). A screening tool for control potential should therefore make it easy for utility planners and operators to understand the exact implications of a potential control implementation, and facilitate dialogue and a common language between employees from different professions and departments.

Control potential indicators are commonly presented in aggregated form in the literature. Fig. 5 demonstrates the spatially explicit representation embedded in COPOTO visualised for an actual case, where real-time control of two actuators will allow the activation of a storage structure to reduce a downstream CSO. This visualisation is implemented in QGIS and provides direct insight into:

1. Where CSO can be reduced and how much. The user can choose for which CSO location results should be displayed. This enables, for example, the filtering of results to identify whether surface waters of particular concern can be protected using real-time control.
2. Which storage structures can be used to achieve reductions at a particular CSO location, and which actuators need to be activated to use this storage. This makes it straightforward for users to discuss, for example, operational and cost-related objectives, and to identify further steps.

Based on the discussions in the performed workshops, planners might consider validating the hydrodynamic model in a promising location (turning an intangible sense of "*the quality of the model is not sufficient*", into a tangible action of "*where should we improve model results*"), or identify control locations where rehabilitations are planned already (leading to reduced investment cost). Furthermore, operators will typically be able to pinpoint whether controlling the considered actuators is feasible or not, and whether sensors are easy to install and maintain in the considered locations (important for, for example, the perception of hassle).

We experienced that the spatial representations immediately foster discussion about concerns that the different stakeholders may have, which otherwise may not take place until later planning stages. Fostering these discussions can help to avoid problems with internal collaboration described in 3.2.

4.1.2. Integrating the screening of control potentials into planning processes that take place already

As outlined in the introduction, the purpose of COPOTO is to provide a qualified guess for control potential in early planning stages, thus lowering the barrier towards the decision whether control should be pursued further as one among several other design options. In the stakeholder process, the utilities were presented both with visualisations of static indicators of their catchments, as well as with a summary of dynamic simulation results (Table 4A+B). In both cases, the utilities were unable to decide for or against further investigations into control,

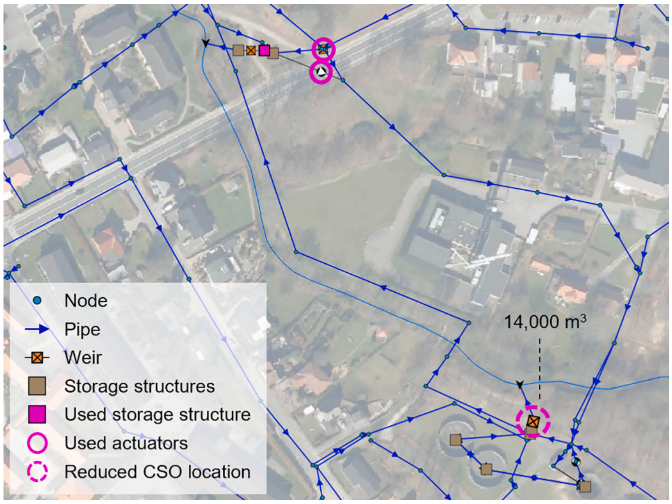


Fig. 5. Real-time control potential visualization generated by COPOTO. Indicators are presented in a spatial context (i.e. which exact CSO location experiences reduction, pink dashed circle with 14,000 m^3 reduction) alongside information on which storages (pink storage structure) and actuators (pink full circles) need to be activated to achieve this. CSO reduction potentials are derived as total reduction over the considered rainfall series that is achieved by activating the actuator and storage in question.

because it was not clear where exactly control should be implemented and what would be the likely outcome. While an experienced planner may have sufficient system insight to derive, for example, suitable control locations from these results, our experience is that this cannot be taken for granted. This is supported by Fig. 6, which illustrates that the potential of reducing CSO volumes that the six utilities expected in the beginning of the project matched the results of COPOTO well in some cases and completely not in others.

If utilities cannot decide from static indicators or an analysis of dynamic simulation results whether control is a reasonable option to consider when redesigning a part of their network, then they need to initiate a separate modelling study for this purpose. Such an analysis may involve choosing control locations (discussed further in Section 4.1.3), implementing a (pre-configured) control algorithm and possibly also the development of a conceptual model. This can easily look overwhelming if no prior indication of the potential outcome is available. COPOTO fills this gap by providing an estimate of control potential related to individual storages and CSO locations whenever a time series simulation in a distributed model has been performed. The method automatically postprocesses hydraulic simulation results in a similar manner as an experienced user with strong system insight probably would, but it is a screening method which has limitations (Section 4.2) and therefore does not remove the need to qualify the assessment in subsequent modelling studies as outlined by (Schütze et al., 2008).

4.1.3. *Getting a first idea of the optimal complexity of a required control scheme*

Real-time control schemes often have many degrees of freedom in terms of how many actuators should be implemented in an existing system and where. Generating such insights so far required the development and simulation of control schemes considering a variety of combinations of potential actuators for the catchment in question (Langeveld et al., 2013; Leitão et al., 2018; Eulogi et al., 2022). This is a tedious process that can take months to complete and that requires a highly specialised workforce. COPOTO can generate such information within hours based on a distributed model simulation that anyway need to be performed. As examples, COPOTO generates the results shown in Figs. 7 and 8. Fig. 7 illustrates that some catchments only have control potential when constructing new actuators, while in other catchments almost the full potential can be realized without any additional construction measures. Fig. 8 illustrates that large parts of the CSO reduction potential in a catchment can usually be achieved by activating a small number of storages. By providing easy access to control potential considering both individual storages as well as combinations of storages, COPOTO facilitates a stepwise implementation of the proposed control locations, which makes the process more manageable and the learning curve less steep for the employees.

4.2. *Limitations*

The methodology for screening CSO reduction potentials presented in this study is subject to a number of limitations that are outlined in the following:

1. COPOTO was developed in a collaborative process with six Danish utilities. While the drivers and barriers for control vary from case to case, COPOTO enables an easy identification of possible locations for control and subsequently a dialogue about other objectives than CSO reduction. While we regard our method to be valid for utilities that operate in a similar context, other needs may arise for water managers operating in, for example, other climatic or cultural contexts, or contexts where distributed urban drainage models are not generally available.
2. Various assumptions have been made in relation to COPOTO, which naturally affect the control potential results. This includes the calculation of transport time and backwater effects on CSO. Both concepts, and especially backwater, are complex phenomena and their exact quantification and impact are beyond the scope of a simple screening. Additionally, certain control actions have not been included, for example the emptying of storage structures prior to CSO occurrence, or the increase of weir levels to increase storage volumes. Finally, the tool does not currently evaluate whether increased emptying times resulting from the proposed activation of storages result in a reduced available storage in subsequent events.
3. Whether the control potential can be realised depends on the chosen control strategy and varies between individual rain events (van der Werf et al., 2021). If the strategy relies on rain forecasts, their quality will naturally also be a factor. COPOTO assumes “perfect control” which means that we, for example, start retaining water in upstream storage structures at the perfect point in time to avoid a downstream CSO and stop filling the storage structure once it is just full. This will naturally overestimate the control potential. At the same time, many of the assumptions have been implemented in a conservative manner that will contrarily underestimate the potential. Which one of these are dominating remains to be investigated in a systematic validation of the control potential against actual control strategies, which is the

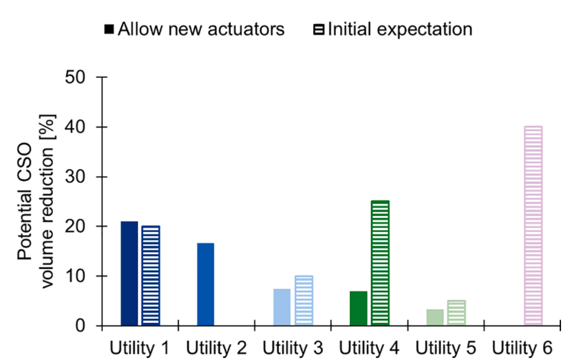


Fig. 6. CSO volume reduction potential in the six case areas when allowing new actuators compared to the CSO volume reduction expected by the utilities in the project startup phase (there was no estimate for Utility 2, and Utility 4 estimated it was “less than 50 % but a lot”; thus 25 % is shown as a conservative interpretation).

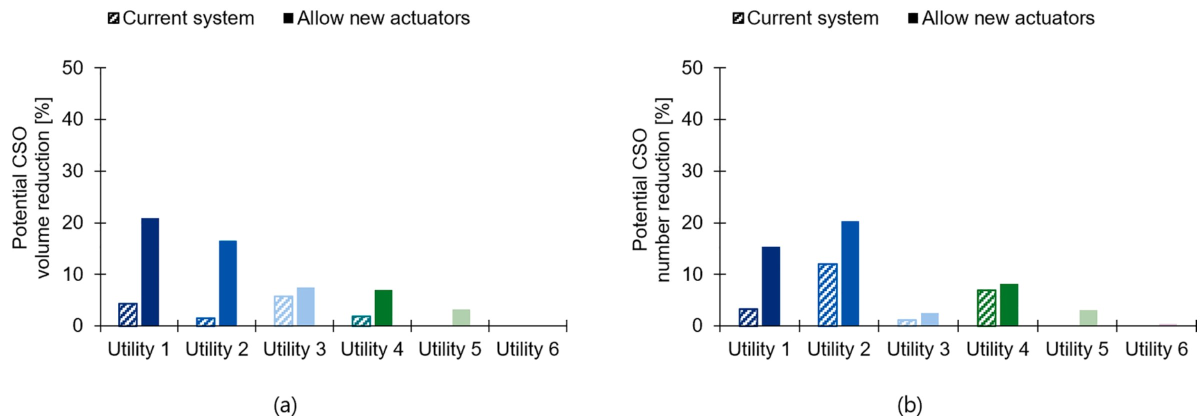


Fig. 7. CSO reduction potential in the six case areas without and with the option of including new actuators. (a) CSO volume reduction (b) CSO number reduction. Utility 6 cannot reduce any CSOs neither without nor with new actuators.

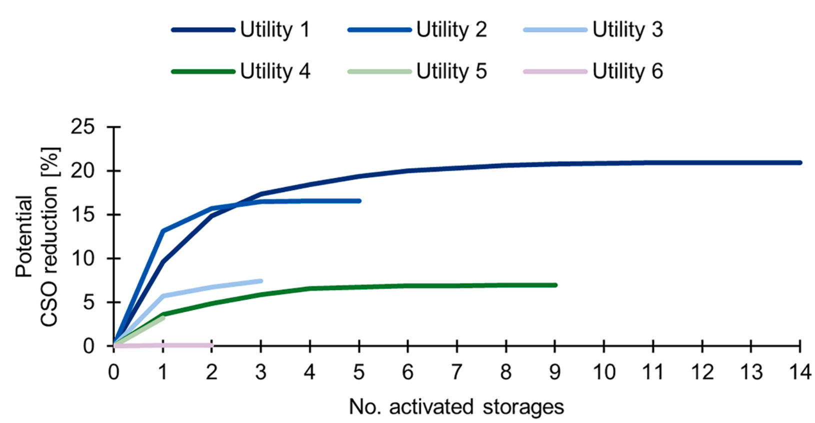


Fig. 8. CSO volume reduction potential (when allowed to insert new actuators) as a function of the number of activated storage structures. The activation of a single storage structure may benefit multiple CSO locations.

next step of the RTC planning process (Schütze et al., 2008). Implementing 'equal filling degree' control strategies based on the storages highlighted by COPOTO in two of the case areas suggests that COPOTO provides reasonable and conservative estimates of control potential (see Supplementary Information A.6). While more investigations are needed, this underlines that COPOTO can provide insight into where CSO can likely be reduced and what measures should be investigated to achieve these reductions.

4. The CSO reduction potentials computed in this study are based on a radar rainfall series of four years. These potentials may therefore not exactly reflect the "true" CSO statistics (that can be obtained by simulating a longer period), but mismatches with operator guesses in Fig. 6 are caused by misunderstandings of which storage volumes can be activated by a control scheme and therefore highly unlikely to change when considering longer time series.

4.3. Outlook

COPOTO calculates the potential CSO reduction and supports dialogue about a range of other objectives that could be relevant in the particular case, for example, the feasibility of actuator implementations, expected maintenance, on-going renovations in the area, or similar. It would be relevant to extend the tool with automated assessments of the expected cost (Dirckx et al., 2011) or CO_2 emissions (Brudler et al., 2016). In addition, it would be relevant to extend the assessment of control potential to other operational goals, such as reducing the peak inflow to WWTPs (Seggelke et al., 2013), controlling surface retention (Lund et al., 2019), or reducing pumping when electricity is expensive (Stentoft, 2020).

5. Conclusions

This paper develops a methodology for screening the potential reduction of CSO volumes using real-time control. The development is embedded into a review of the existing literature and a co-design process with six Danish utilities that guided the choice of indicators as well as the final screening methodology. A basic premise was that the tool should take advantage of the widely available distributed urban drainage simulation models, but at the same time be computationally fast enough to support the workflow of water managers.

We have come to the following conclusions:

1. The participating utilities considered previously published CSO reduction indicators not based on urban drainage model simulations as insufficient. Indicators based on static system attributes can thus not stand alone, and a practical and fast method that estimates CSO frequencies and volumes from model simulations without manual effort was found to be missing.
2. Most scientific literature on real-time control considers only environmental and economic objectives that are aggregated on catchment level, for example, total reduction in CSO volume and total cost of solutions. However, the motivations and barriers for implementing real-time control are manifold and include environmental, economic, social, and technical aspects. CSO reduction results are irrelevant for utilities if they cannot relate these to the other objectives.

3. Following the previous point, the participating utilities preferred a presentation of CSO reduction potentials in a spatial setting that illustrates both the locations where CSO reductions are achieved and the actuators and storage structures that need to be controlled to do so. This visualisation fosters an immediate dialogue about locally important objectives, for example, whether technical constraints arise at the suggested location.
4. The new screening tool computes the CSO reduction potential by post-processing the results of distributed urban drainage simulations for a single rainfall time series. The algorithm accounts for the spatial structure of the network, and automatically finds the unused storage during rain events. Potential CSO reduction is visualized in a spatially distributed manner. The fast post-processing enables a straightforward integration of control potential assessments into common planning workflows. Instead of needing to perform separate studies on control potential, utilities can get an initial, realistic assessment whenever, for example, the construction of a new storage structure is considered. The automatic post-processing breaks down a major barrier in relation to the (perceived) complexity of real-time control and lacking system overview. In addition, previously tedious analyses such as determining the optimal number of actuators now become practically feasible.
5. We can identify a clear mismatch when comparing the control potential determined in our case studies against the initial guess of the stakeholders. This underlines the need for a systematic control potential quantification.
6. Improved screening of control potentials does not remove the need for a subsequent development of a control algorithm and the assessment of its effectiveness in model simulations.

CRediT authorship contribution statement

N.S.V. Kirstein: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **P.S. Mikkelsen:** Conceptualization, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **M. Rungø:** Conceptualization, Methodology, Project administration, Supervision, Writing – original draft, Funding acquisition, Resources. **R. Löwe:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nadia Kirstein and Morten Rungø reports financial support was provided by Envidan. If there are other authors, they 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 source code is the intellectual property of Envidan and is thus not open source.

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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.2024.121527.

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