Water Science & Technology

Water Science & Technology Vol 90 No 1, 168 doi: 10.2166/wst.2024.191

Metrics to quantify the degree of co-location of urban water infrastructure

Shamsuddin Daulat [a,b,]*, Bardia Roghani [a,c], Jeroen Langeveld [d], Marius Møller Rokstad [a] and Franz Tscheikner-Gratl [a]

[a] Department of Civil and Environmental Engineering, Faculty of Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] Klepp Kommune, Solavegen 1, Kleppe 4351, Norway
[c] Water and Environmental Engineering, Institute of Civil and Environmental Engineering, Norwegian University of Life Sciences (NMBU), Ås, Norway
[d] Faculty of Civil Engineering and Geosciences, TU Delft, Delft, the Netherlands
*Corresponding author. E-mail: shamsuddin.daulat@klepp.kommune.no

SD, 0000-0001-7385-4195; BR, 0000-0001-5435-6748; JL, 0000-0002-0170-6721; MMR, 0000-0003-4650-3554; FT, 0000-0002-2545-6683

ABSTRACT

Co-located infrastructure networks such as road, water, and sewer in theory offer the possibility for integrated multi-infrastructure interventions. However, how closely these networks are aligned in space and time determines the practical extent to which such coordinated interventions can be realized. This study quantifies the spatial alignment of the aforementioned infrastructure networks and demonstrates its application for integrated interventions and potential cost savings. It proposes two metrics, namely 1) shared surface area and, 2) shared trench volume, to quantify the spatial relationship (i.e., degree of co-location) of infrastructures. Furthermore, the study demonstrates how the degree of co-location can be used as a proxy for cost-saving potential of integrated interventions compared to silo-based, single-infrastructure, interventions. Through six case studies conducted in Norwegian municipalities, the research reveals that implementing integrated interventions across road, water, and sewer networks can result in potential average cost savings of 24% in urban areas and 11% in rural areas. Utility-specific savings under different cost-sharing scenarios were also analysed. To identify the yearly potential of integrated multi-infrastructure interventions, future work should add the temporal alignment of rehabilitation of infrastructures (i.e., time of intervention need for the infrastructures).

Key words: cost sharing, degree of co-location, infrastructure interdependency, multi-utility asset management, neighboring assets

HIGHLIGHTS

- The 'degree of co-location' quantifies the spatial relationships among infrastructure networks.
- An application of the degree of co-location can be its use as a proxy for economic and environmental savings of integrated interventions.
- On average, 24% cost-saving potential for multi-utility interventions in urban areas.
- On average, 11% cost-saving potential for multi-utility interventions in rural areas.

LIST OF SYMBOLS

R	Road trench
R_a	Road trench surface area
R_v	Road trench volume
S	Sewer pipe trench
S_a	Sewer trench surface area
S_v	Sewer trench volume
W	Water pipe trench
W_a	Water trench surface area
W_v	Water trench volume
St_a	Stormwater trench surface area
St_v	Stormwater trench volume
Sf_a	Foul sewer trench surface area
Sf_v	Foul sewer trench volume
Sc_a	Combined sewer trench surface area

Sc_v Combined sewer trench volume
rca Reduced cost of surface reconstruction
rcv Reduced cost of trenching
csp Cost-saving potential

1. INTRODUCTION

Urban infrastructures, like water distribution, sewer, and transportation networks are vital for cities, supporting social and economic activities. They are also interconnected, meaning that disruptions in one infrastructure system can affect another. For example, maintenance on water networks might result in road closures and transportation delays. The traditional silo-based methods of managing these infrastructures separately may therefore miss opportunities for sustainable asset management (Jayasinghe *et al.* 2023). The degree to which infrastructure systems are interdependent plays a critical role in both their resilience and vulnerability, as noted by Zischg (2018). This interconnectivity is crucial for effective infrastructure asset management. Overlooking the interconnected nature of urban infrastructure systems can lead to suboptimal management practices (Araya & Vasquez 2022).

Moreover, with changing boundary conditions caused by climate change, growing urban populations, and stricter environmental rules, utilities are more and more under pressure to address rehabilitation and adaptation needs. Complying with mandates like the Drinking Water (European Commission 2020) and the Urban Wastewater Treatment (European Commission 1991) directives, the 28 EU member states are expected to spend a total of EUR 289 billion more by 2030 on water supply and sanitation (OECD 2020). As the Urban Wastewater Treatment Directive 91/271/EEC of 21 May 1991 (European Commission 1991) is currently under revision (Directorate-General for Environment 2022), costs might rise even more because of increasing performance requirements. Therefore, infrastructure managers need efficient methods to allocate their restricted budgets for managing assets in a cost-effective manner and cannot ignore the cost-saving potential (CSP) provided by coordination with other adjacent infrastructures. A fiscally prudent approach involves the implementation of a coordinated infrastructure management strategy (Saidi *et al.* 2018; Abu-Samra *et al.* 2020).

The coordinated management of several infrastructure components in the most effective way is referred to as integrated multi-infrastructure asset management (IMAM) (Daulat *et al.* 2022; Shahata *et al.* 2022). Such integration reduces operational activities, minimizes disturbances, and cuts intervention expenses (Metayer *et al.* 2020). The community also benefits from reduced traffic disruptions and shorter service interruptions. Coordinated multi-infrastructure management is also reported to encourage structured data management, enhancing transparency and public accountability (InfraGuide 2005). Further, an often-overlooked advantage of IMAM during an intervention is preventing partial repair of roads, which can normally happen in silo-based interventions. The partial repair of roads affects the quality of the whole road segments (Torbaghan *et al.* 2020).

Multi-utility tunnels, as game changers, facilitate maintenance activities without the need for excavations by housing various utility networks in a common space, which allows for better-integrated management of urban infrastructures (Hunt *et al.* 2014; Luo *et al.* 2020; Nieuwenhuis *et al.* 2021). However, the construction of such tunnels is primarily limited by the need for substantial initial investments (Hunt *et al.* 2014). Additionally, Nieuwenhuis *et al.* (2021) argue that such integrations may result in higher uncertainties.

In both industry (e.g., Selvaggio *et al.* 2018; Taaveniku *et al.* 2019) and academia (e.g., Tscheikner-Gratl *et al.* 2019), there is an increasing awareness of the necessity for an integrated approach to infrastructure management. Still, contrary to individual infrastructures, the development of IMAM models has not received much attention in the literature (e.g., Kielhauser 2018; Kammouh *et al.* 2021; Pericault *et al.* 2023). This lack of uptake, and the reasons behind it, have been discussed by Daulat *et al.* (2022), who identified and highlighted the challenges to its adoption, namely data quality, availability and interoperability, uncertainties, comparability, problems of (spatial and temporal) scale, fit and interplay as well as understanding cost savings, and system interdependencies. Some of those challenges have been addressed in the past. Halfawy (2010) presented a framework for integrating urban water and wastewater infrastructures, emphasizing federated models as ideal for IMAM, despite data fragmentation challenges. Metayer *et al.* (2020) introduced a framework for integrated municipal infrastructure management. This framework, composed of three modules, considers cost reductions from co-located infrastructure maintenance. Testing on an urban pavement and sewage network revealed a 9% maintenance cost reduction with IMAM. However, they recommended further research on real municipal networks to provide more precise estimates. Kielhauser

& Adey (2020) proposed a method for determining optimum intervention plans for multiple infrastructure networks. Although they discussed potential benefits, no empirical results were provided. Marzouk & Osama (2017) suggested an approach to assess the condition of various infrastructure assets, including water, sewer, and roads. Their multi-objective optimization focused on risk, infrastructure condition, service level, and life cycle costs. Applying this to the city of Zahraa El-Maadi, Egypt, revealed that over 86% of intervention projects favored an integrated approach.

Furthermore, most research focused on the tactical management level for multi-utility coordination, and less focus is devoted to the strategic management level (Daulat *et al.* 2022). Examples of tactical level management include studies by Abu Samra *et al.* (2018), Carey & Lueke (2013), Osman (2016), Shahata *et al.* (2022), and Tscheikner-Gratl *et al.* (2016), which aim for optimal scheduling and maximizing reinvestment budgets. Recent findings show that utilities view cost saving via IMAM as highly beneficial (Araya & Vasquez 2022). However, quantification of the CSP in IMAM, especially utility-specific savings, is missing in the literature. Techniques like quantity discounts (Nafi & Kleiner 2010; Rokstad & Ugarelli 2015), grouping optimization models (Li *et al.* 2016), and adjacency criteria (Roshani & Filion 2014; Kerwin & Adey 2020) consider cost reductions but have limitations on larger networks due to computational demands.

To objectively get an insight into the saving potential of integrated interventions and into the spatial relationship of infrastructure networks, uniform metrics (or proxies) for integrated interventions of a variety of infrastructures are needed. Gaining insights into these spatial relationships is crucial for comprehending the physical interactions between infrastructures, which can be a key component of any infrastructure asset management strategy, including water infrastructure asset management (Le Gat *et al.* 2023). A way to approach this is by looking at the problem of spatial scale and fit (Daulat *et al.* 2022). It is based on the inconsistencies in size (spatial scale) and geographic co-location (fit) of different infrastructure assets that can hinder a smooth application of IMAM. On the other hand, insights into the scale and fit inconsistencies can also provide valuable information on how successful and beneficial IMAM can be. Until now, IMAM literature (for an overview, see Daulat *et al.* 2022) has mainly abstracted the scale and fit inconsistencies into a binary state; either no inconsistencies exist (perfectly co-located) or fully inconsistent (not co-located at all). The former is an assumption allowing the usage of street sections as a container for all infrastructure networks (Tscheikner-Gratl *et al.* 2016).

Islam & Moselhi (2012) introduced a computational method for determining geographical interdependency among assets, using Geographic Information System (GIS) for introducing the degree of co-location. The study may be utilized as a starting point for gathering information to facilitate decisions on co-located assets. However, the study's focus is limited to surface area co-location and does not delve into three-dimensional (volume) analysis of co-location. In combination, the surface area and volume co-location can determine the amount of work shared between the infrastructures during an intervention, helping in objectively quantifying cost sharing among the utilities.

In an integrated intervention, the shared surface area and volume of the trenches of different infrastructure networks highlight the reduced workload. The reduced workload associated with shared volume can include, for example, excavation, soil movement, backfilling, and compacting. Likewise, the shared surface area workload reduction may include, for example, surface removing, resurfacing, and road marking. Hence, the shared surface area and volume can quantify the cost savings of an integrated intervention. Similarly, they can quantify carbon savings and the extent of road closures. Higher co-location degrees suggest greater savings potential. An exception to this is trenchless methods (Jung & Sinha 2007). Notwithstanding this limitation, a holistic quantification and evaluation of the shared surface area and volume of trenches among the infrastructure networks is not carried out in the literature.

By evaluating the shared surface area and volume on a network level, this paper aims to contribute to the understanding of three-dimensional spatial relations of infrastructure networks by defining and assessing the degree of co-location. Additionally, the paper aims to demonstrate an application of the degree of co-location that is useful for coordinated multi-infrastructure asset management. The metrics of the degree of co-location (i.e., shared surface area and volume of trenches) are used to quantify the overall and utility-specific CSP during integrated interventions involving road, water, and sewer systems. These networks are selected due to their dominance in cost of replacement per unit length, compared to other networks, such as electricity and data cables (Tscheikner-Gratl *et al.* 2017b). Using data from various Norwegian municipalities, the study also examines how the degree of co-location varies between urban and rural areas, investigating potential differences across these contexts. Another application of the degree of co-location can be realized by connecting it to deterioration models of the networks to create a spatiotemporal model of the networks. The spatiotemporal model can be used for identifying and planning integrated intervention projects. However, creating a spatiotemporal model and demonstrating its applications is out of the scope of this paper.

The proposed research methodology primarily involves calculating the metrics and demonstrating how these metrics can be used for the CSP of integrated interventions. First, the coordinates of the assets are converted into trench coordinates using available guidelines for trench excavation. Based on the guidelines, two cross-section shapes, depending on the depth of the trench, are considered. For shallow excavations, i.e., less than 2 m deep, rectangular cross sections with side slopes at 90° were used. For deep excavations, i.e., 2 m or deeper, trapezoidal cross sections with side slopes at 45° were used. The modeled trenches of different infrastructure assets are then intersected using open-source Python libraries suitable for processing 2D and 3D objects, specifically GeoPandas (Jordahl *et al.* 2023) and Geometry3D (Gou 2021). GeoPandas extends the capabilities of pandas to facilitate the handling of 2D and simple 3D geographic objects. Geometry3D is utilized for processing complex 3D objects when GeoPandas is insufficient for such tasks. The use of shared trenches as proxies for cost savings is based on avoiding the need for repeated excavation and resurfacing of the shared trenches due to integrated interventions, which would otherwise occur if separate interventions were carried out on individual infrastructure assets. The CSP of an infrastructure is determined by the proportion of its shared trench network with other infrastructures and their agreement on cost distribution. The entire process is automated by developing Python scripts, except the separation between urban and rural areas which was done manually using a GIS interface. Hence, the methodology is semi-automated.

2. MATERIAL AND METHODOLOGY

For assessing the degree of co-location of infrastructure networks during an intervention, this section presents a method of quantifying the shared surface area and volume of assumed open trench excavations. Moreover, an approach for calculating the potential of cost savings of integrated interventions on a network level is suggested.

For simplicity, the following notations are used in this study: R_a denotes road trench surface area, S_a denotes sewer trench surface area, W_a denotes water trench surface area, R_v denotes road trench volume, S_v denotes sewer trench volume, St_v denotes stormwater trench volume, Sf_v denotes sewage (foul sewer) trench volume, Sc_v denotes combined sewer trench volume, and W_v denotes water trench volume. It is important to note that the term 'sewer' (or S) in this study refers to the combination of its constituent components, namely stormwater (St), sewage (Sf), and/or combined sewer (Sc) (i.e., $S = \mathrm{St} \cup \mathrm{Sf} \cup \mathrm{Sc}$), unless explicitly stated otherwise.

We assume that separate and combined sewer systems do not exist under the same road and therefore $(\mathrm{St} \cup \mathrm{Sf}) \cap \mathrm{Sc} = \emptyset$, although there are a few exceptions to that rule. For a network-level calculation, the impact of ignoring those few cases is not significant on the results. Moreover, it is assumed that sewer (consisting of both separate and combined systems), water, and road are each an independent utility with independent budgets. This will allow us to calculate the CSP for each utility separately and, if necessary, the method can easily be adapted to include other utilities.

2.1. Data description

For this study, data on trench dimensions and georeferenced locations were sourced from six Norwegian municipalities, encompassing GIS coordinates, depths, and diameters/widths of pipes and roads. The municipalities are small- to medium-sized municipalities located in mid-, south-east, and south-west Norway. The total combined length of roads, water, and sewer pipes studied in this study are 9,987, 6,512, and 9,390 km, respectively. Figure 1 details individual municipality's as well as the total length of assets utilized in this study.

The reliability and accuracy of this work rely on the availability and quality of the input data. The quality of the geolocation data (X, Y, Z) is characterized as the difference between the locations shown by the data and their actual positions. Larger differences ($>$0.5 m) are typically due to differences between design and as-is, and where design data are used in the records. Smaller differences ($<$0.5 m) may be due to the measurement uncertainty of the surveying equipment. These differences can be considered negligible for this study. Rectifying differences between design and construction in retrospect is a daunting task, requiring extensive and often impractical inspection and survey efforts (Ottenhoff & Korving 2007). Therefore, this source of uncertainty was ignored in this study.

The primary missing data pertains to the absence of depth information for pipes. Depending on the municipality, the missing depth data range from 69 to 98%, except for municipality 2, where only 39% of depth data are missing. However, the planimetric geolocation – representing the X, Y coordinates – is largely intact. To address the missing depth data, we utilized local guidelines for pipe depth as a basis for estimation. We explored three scenarios, where missing pipe data were filled with minimum, average and maximum recommended depths. By utilizing these available data

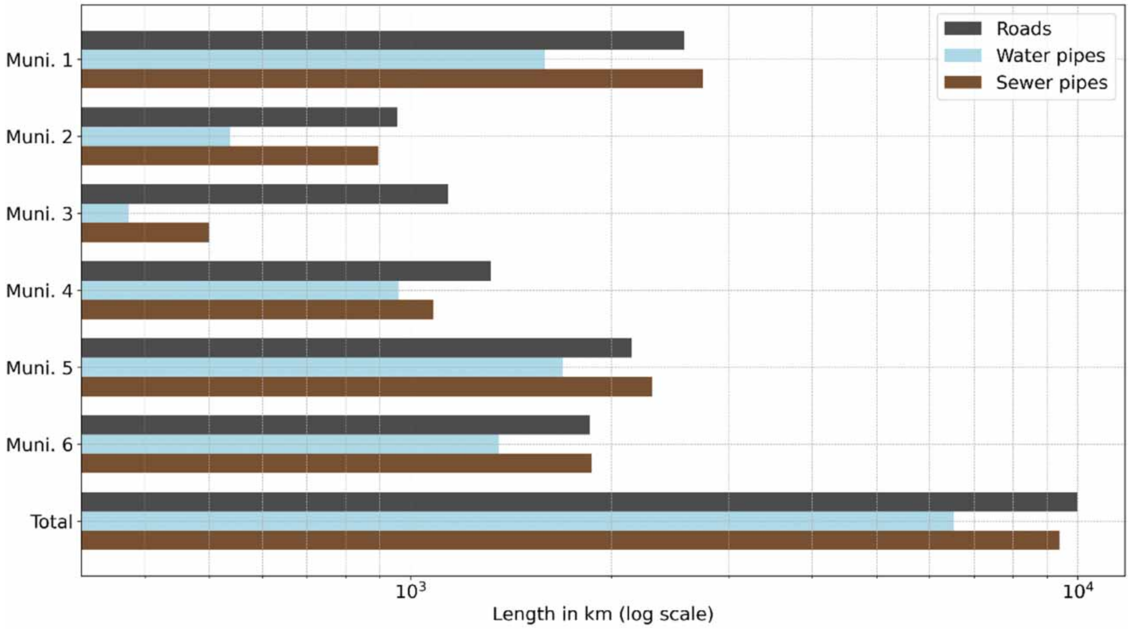

Figure 1 | Length of assets in each municipality and in total.

and following the national and local guidelines (e.g., Norsk Vann 2004) on trench shapes and dimensions, one can obtain the necessary trench dimensions and their corresponding georeferenced corners. The methodology is illustrated in a flow char in Figure 2.

It should be noted that among the data collected on roads, the construction height of the roads, comprising both the foundation and the road surface, referred to as 'road depth' in this study, was also not directly available. Depending on each specific project, road depth may vary. According to Huang (2004), road depth can range from 43 to 105 cm, depending on load, economy, and number of layers (i.e., surface layer, binder layer, base layer, subbase layer, compacted subgrade layer) considered. This range aligns with Norwegian standards (Statens Vegvesen 2022), though individual road depths may vary based on local conditions. In this study, similar to pipes, minimum, average, and maximum depths were used to explore the variations in the degree of co-location and CSP. Moreover, the road surface areas exclude road-side parking, off-street parking, areas inside roundabouts and green spaces between two-way roads.

2.2. Calculating shared trench surface areas and volumes

To calculate the shared trench volume/area, there are five steps that need to be taken. Step 0 is preprocessing data so that it can be later used for intersection using Geometry3D. In step I, the coordinates of sewer/water pipe trenches are calculated based on the coordinates of their respective pipes. The coordinates of the road trench are the coordinates of the road surface area and bottom area at the road depth (43 cm for minimum, 75 cm for average, and 105 cm for maximum depths). In step II, polygons are created to represent the trench at the surface level and at the invert level, using the Buffer function in GeoPandas. In step III, an intersection between the trenches is carried out using GeoPandas or Geometry3D, and in the last step, the overall shared trench area and volume between infrastructures are calculated.

2.2.1. Split pipes into linear segments

This step is a preprocessing measure to render the data compatible with Geometry3D processing in subsequent steps. We utilized both GeoPandas and Geometry3D libraries in the methodology due to their respective strengths and limitations. GeoPandas is efficient at processing 2D or simplified 3D objects (such as calculating volumes by multiplying area by height). However, it falls short of processing complex 3D objects, for instance, intersected trench volumes of sewer and water where the height of the intersection is not initially known. This is where Geometry3D comes in; it can model and process complex 3D shapes but is limited to convex forms and is less efficient. Therefore, we have established protocols to avoid using concave shapes with Geometry3D. As the first protocol, pipes are split into linear segments in this step. As pipes

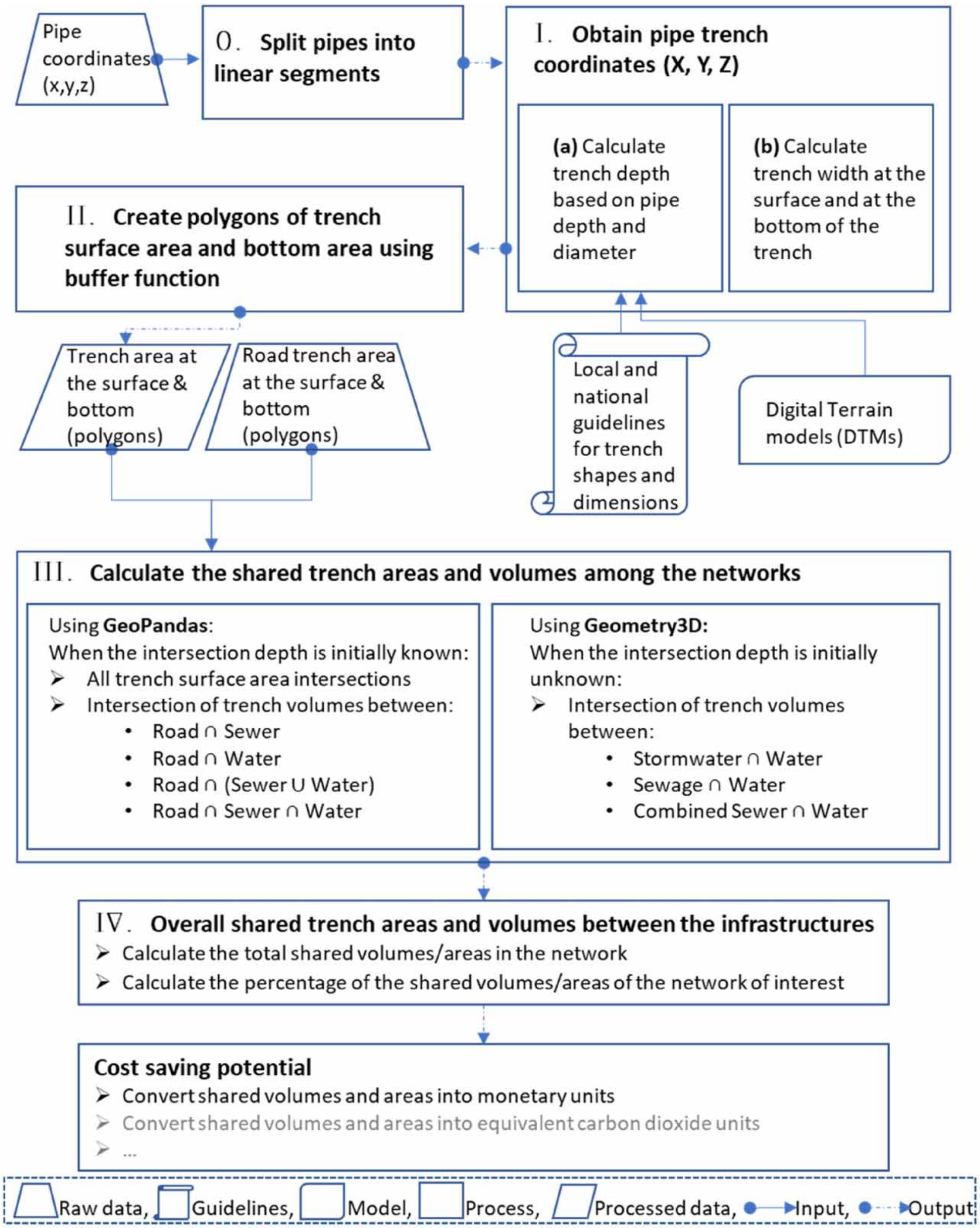

Figure 2 | A flow chart outlining the methodology steps involved from processing the data to calculating the shared trench volumes/areas and cost-saving potential.

are often series of connected pipe segments with corners and bends, directly translating pipe coordinates into trench coordinates yields concave shapes. Therefore, by splitting the pipes into linear segments (as shown in Figure 3), the creation of concave trench shapes is avoided. In this approach, each straight segment of a pipe is treated as an independent entity, instead of viewing the entire pipe as a single, unified structure. This step ensures compatibility with Geometry3D, without compromising the processing capabilities of GeoPandas.

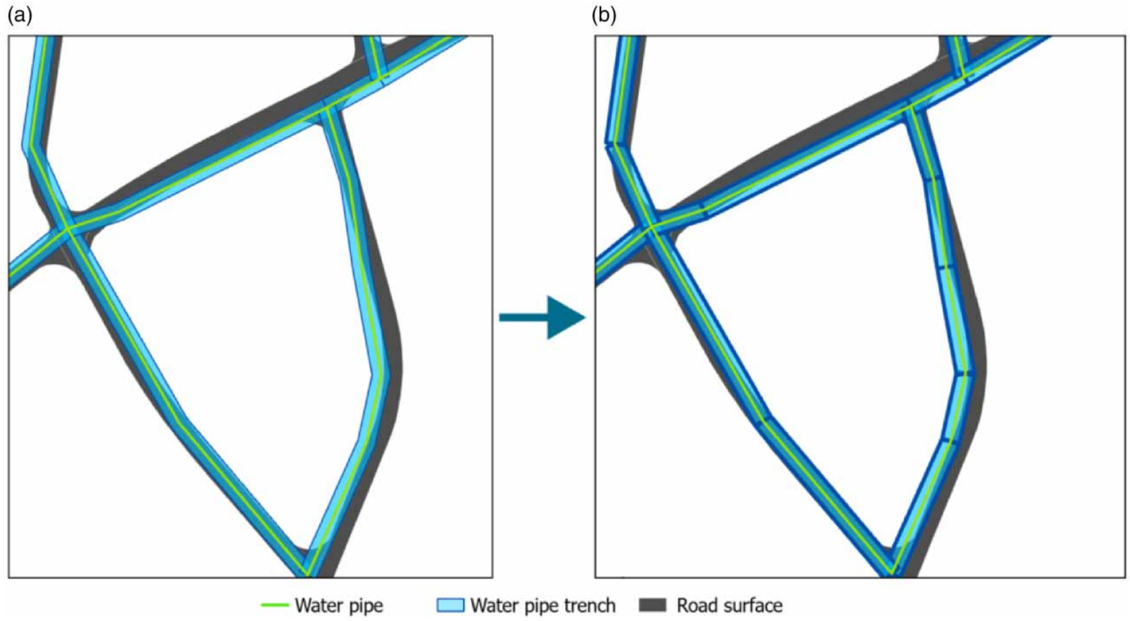

Figure 3 | Illustration of converting (a) bended water trenches into (b) straight water trenches to avoid concavity.

I. Obtain sewer/water trench coordinates (X, Y, Z)

This section describes how to calculate the coordinates of trenches for sewer/water pipes based on the coordinates and diameters of the pipes and the recommendations from the local guidelines (Norsk Vann 2004).

Starting with depth in step (a), trench depths (d_t) are calculated based on the pipe depths (d_p) using local guidelines (see Appendix 7.1, available online). For example, the bottom of the trench should be at least 150 mm below the bottom of the pipe, resulting in $d_t = d_p$ (pipe depth) + diameter/2 + 150 mm. However, pipe depths are not directly available in the database and are approximated by the manhole depths where available. Around 2–98% of the manhole heights at the surface and at the invert level are available in the database for each utility. In cases where the surface elevations of the manholes were missing, digital terrain models (DTMs) were used to fill in the missing values. The manhole depth is then calculated as the manhole elevation at the surface minus the invert elevation. In cases where invert elevation is missing, standard values were used which are provided by the local guidelines (Norsk Vann 2004). The guidelines state that pipes should be between 1.5 and 2.5 m deep. Therefore, an average of 2 m was used for missing water pipe depths (1.5 m for the minimum scenario, and 2.5 m for the maximum scenario). Subsequently, the depths for sewer pipes, manholes and trenches were calculated in accordance with the guidelines on distances of pipes in a trench (Norsk Vann 2004).

In step (b), the trench widths at the surface and bottom are calculated. The width of the trench depends on the trench depth and the slope (α), see Appendix 7.1. According to Norsk Vann (2004), α should be 45° if the d_t is 2 m or more, in other cases the slope should be based on site-specific conditions (e.g., soil conditions). Based on security rules for excavation works, 90° was used for α if d_t was less than 2 m, and 45° otherwise, as site-specific data for individual trenches was not available.

II. Create polygons using the buffer function

The estimated trench width attribute calculated in the previous step is buffered to geometrically represent the width of the trenches in the GeoPandas GeoDataFrame. The output of this step is a set of sewer/water pipe trench areas in polygon format, representing the surface and invert area for each trench. This output format is the same as the available road data (polygon shapefiles), allowing for joint processing and analysis.

III. Intersect the trenches to calculate the shared trench areas and volumes

Once the trench polygons were ready for intersection, we used two Python libraries to calculate the shared area/volume between the trenches. For surface area intersections and for volumes where the depth of intersection is fixed and does not

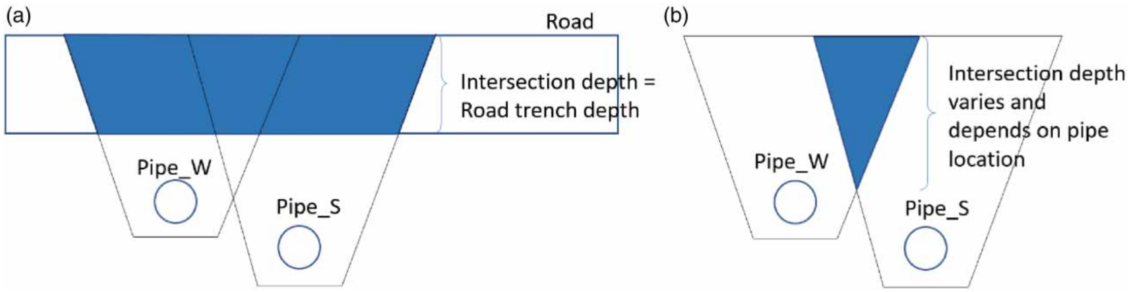

Figure 4 | An illustration of (a) fixed and (b) varying intersection depths.

vary from case to case, GIS functions, using GeoPandas, were used to calculate the area/volume intersection between these trenches. In this category, all two-dimensional intersections, and some volumetric intersections are included, namely those volumetric intersections of a road with sewer/water ($R_v \cap S_v$, $R_v \cap W_v$), and the intersection of a road with union of sewer and water ($R_v \cap (S_v \cup W_v)$) (e.g., Figure 4(a)), as the depths of these intersections are determined by the depth of the road trench depth. In such cases, the intersected trench shape from the front view is trapezoidal and its volume can be calculated by averaging between the top and bottom area and then multiplying it by the depth of the intersection, which is the road trench depth (see Figure 4). Three GIS functions in GeoPandas were mainly used for data processing and volume calculations: 1. Dissolve, to avoid overlaps of the trenches from the same utility (e.g., St and Sf are dissolved to obtain S), 2. Clip, which represents the intersection (∩) between trench volumes, and 3. Union, which represents the union (∪) of trench volumes.

There are three other cases where the depth of the intersection is not fixed and varies depending on the X, Y coordinates of the pipes. These cases are: 1. $S_v \cup W_v$, 2. $S_v \cap (R_v \cup W_v)$ and 3. $W_v \cap (R_v \cup S_v)$ (e.g., Figure 4(b)). In these cases, GIS functions are unable to calculate the volume of the intersection unless each trench is manually modeled in the GIS in three dimensions, which is not practical for a whole network due to the high computational load. To address this limitation, Geometry3D is employed for this calculation. However, before utilizing Geometry3D effectively, two prerequisite steps are necessary for the Geometry3D to function. Firstly, to address the problem of scale (Daulat *et al.* 2022) in cross-asset interventions where a single asset from one infrastructure may intersect with multiple assets of another infrastructure, we employed the Spatial Join (sjoin) function in GeoPandas. This function facilitated the one-to-many intersection in Geometry3D, allowing us to identify the overlapping trenches of sewer and water. Secondly, the trench polygons in the GeoDataFrame format need to be converted into Cartesian coordinates format. This conversion allows Geometry3D to calculate the intersection volume. Notably, since the trench shapes were made convex in the previous steps, Geometry3D is now able to carry out the intersection operation.

However, there is one exception where Geometry3D will not be able to operate and that is the formation of yet again concave shape by unionizing St and Sf (because $S_v = \mathrm{St}_v \cup \mathrm{Sf}_v$) (refer to Figure 5). Even though, St and Sf are individually convex shapes.

In this specific case, we utilized the principle of inclusion-exclusion in set theory to avoid unionizing the two shapes (St and Sf) and hence, avoid creating concave shapes.

Utilizing the principle of inclusion-exclusion, we can write:

$$W_v \cap (\mathrm{St}_v \cup \mathrm{Sf}_v) = (W_v \cap \mathrm{St}_v) + (W_v \cap \mathrm{Sf}_v) - (W_v \cap \mathrm{St}_v \cap \mathrm{Sf}_v)\ [\mathrm{m}^3] \tag{1}$$

where $(W_v \cap \mathrm{St}_v \cap \mathrm{Sf}_v) = ((W_v \cap \mathrm{St}_v) \cap (W_v \cap \mathrm{Sf}_v))$.

Each intersection on the right side of the equations is an intersection between only two convex shapes, which can be carried out by Geometry 3D. Hence, the three circumstances mentioned earlier can be solved in the following ways:

1. $S_v \cap W_v = (\mathrm{St}_v \cup \mathrm{Sf}_v \cup \mathrm{Sc}_v) \cap W_v$

Based on the inclusion–exclusion principle, the right side of the equation is:

$$\begin{aligned}(\mathrm{St}_v \cup \mathrm{Sf}_v \cup \mathrm{Sc}_v) \cap W_v = {} & (\mathrm{St}_v \cap W_v) + (\mathrm{Sf}_v \cap W_v) + (\mathrm{Sc}_v \cap W_v) \\ & - ((\mathrm{St}_v \cap W_v) \cap (\mathrm{Sf}_v \cap W_v)) - ((\mathrm{St}_v \cap W_v) \cap (\mathrm{Sc}_v \cap W_v)) \\ & - ((\mathrm{Sf}_v \cap W_v) \cap (\mathrm{Sc}_v \cap W_v)) + ((\mathrm{St}_v \cap W_v) \cap (\mathrm{Sf}_v \cap W_v) \cap (\mathrm{Sc}_v \cap W_v)) \quad [\mathrm{m}^3]\end{aligned} \tag{2}$$

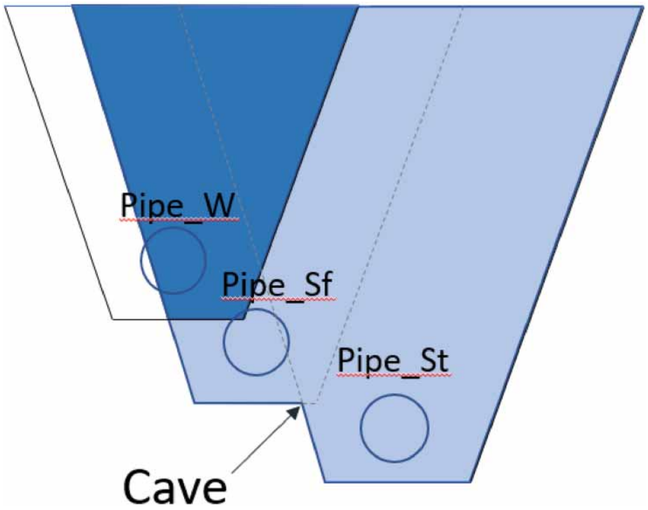

Figure 5 | The concavity problem when stormwater and sewage trench are unionized.

If $(St_v \cup Sf_v) \cap Sc_v = \emptyset$ (separate and combined systems do not intersect each other), then any intersection of St or Sf with Sc is empty. Equation (2) then simplifies to:

$$(St_v \cup Sf_v \cup Sc_v) \cap W = (St_v \cap W_v) + (Sf_v \cap W_v) + (Sc_v \cap W_v) - ((St_v \cap W_v) \cap (Sf_v \cap W_v)) \quad [m^3] \tag{3}$$

Each element on the right side of the equation is a convex shape and hence, the intersection can be calculated using Geometry3D.

2. Similarly, $S_v \cap (R_v \cup W_v) = (S_v \cap R_v) + (S_v \cap W_v) - (S_v \cap R_v \cap W_v)$
In which $(S_v \cap R_v)$ and $(S_v \cap R_v \cap W_v)$ can be obtained using GIS functions, and $(S_v \cap W_v)$ is equal to Equation (3).
3. Similarly, $W_v \cap (R_v \cup S_v) = (W_v \cap R_v) + (W_v \cap S_v) - (S_v \cap R_v \cap W_v)$

Each term of the right side of the equation can be obtained the same way as in 2.

IV. Calculate the overall shared trench areas and volumes between infrastructures

For comparability between different utilities and different network sizes, the sum of the shared areas and volumes across the entire network is normalized, using the total area or volume of the specific network of interest. This will provide the shared areas/volumes of a particular network with another network as a percentage of the total area/volume of the network of interest. For instance, dividing the shared volume of a road trench and a sewer trench $(R_v \cap S_v)$ by a road trench volume (i.e., $(R_v \cap S_v)/R_v$) provides the proportion of the road trench volume that is shared with the sewer trench. Likewise, dividing the shared volume by the sewer trench volume (i.e., $(R_v \cap S_v)/S_v$) yields the proportion of the sewer trench volume that is shared with the road trench. In this way, the asset in the denominator means the intersection is calculated from the perspective of that asset.

To evaluate the degree of co-location in urban and rural settings separately, the networks are divided between urban and rural areas based on the definition provided by Eurostat (2021), since the data itself do not differentiate between urban and rural areas. According to Eurostat, an 'urban' area is identified as a cluster of adjacent 1 km^2 grid cells with at least 300 inhabitants per km^2 and a minimum population of 5,000 inhabitants, while any area that does not meet these criteria is considered 'rural' in this study. The Eurostat definition was used for consistency and reproducibility of the work. Population data of the municipalities studied in this study were collected from the Norwegian geographic database (GeoNorge 2019) and the networks were separated based on the given definitions.

2.3. Cost-saving potential

The degree of co-location has practical applications, for example, it is an important input for quantifying the CSP, as well as the greenhouse gas saving potential of integrated interventions and can therefore serve as a proxy for those values.

The CSP is quantified by translating the shared trench volume and area into reduced workload, and hence, reduced cost. A shared trench volume is the volume that is prevented from being excavated and backfilled multiple times in the case of an integrated intervention. Similarly, a shared surface area is the area that is prevented from being resurfaced multiple times in such interventions. Hence, the shared volume and surface area represent the reduced workload and, consequently, reduced cost in an integrated intervention compared to separate interventions. Because of the assumption that, if there is any degree of co-location, an integrated intervention is always possible (discarding the temporal inconsistencies), calculations show the maximum potential of reduced costs. Therefore, it is called 'cost-saving potential'. This potential is quantified in two steps. First, the reduced cost of volumetric-related work (rcv) and reduced cost of areal-related work (rca) for each asset type is quantified. Then, CSP is quantified by multiplying the 'rcv' and 'rca' by their unit costs and dividing them by the total cost to obtain the result in percentage.

The costs related to shared trench surface area and volume among multiple infrastructures can be divided among the infrastructures involved. The higher the degree of co-location and the number of infrastructures involved, the higher the potential for cost savings. For instance, a trench shared between road, sewer, and water (i.e., $R \cap S \cap W$) has higher CSP than a trench shared only between road and sewer (i.e., $R \cap S$) or road and water (i.e., $R \cap W$). However, it is important to note that the division of costs does not necessarily have to be evenly distributed, as coordination and cost-sharing among the utilities are typically negotiated (van Riel *et al.* 2017a). A CSP model could be used as a tool for negotiation in such situations. Therefore, the CSP model developed in this study considers a cost-sharing factor that is determined through negotiations between the utilities.

The reduced cost of volumetric-related work for road (R_{rcv}), for example, is the proportion of costs incurred by sewer and water. This reduced cost is calculated by assessing the extent to which the road's volume overlaps with sewer and water infrastructures. These shared volumes, when multiplied by cost-sharing factors that show how much of the cost of the shared volume the sewer and water utilities are willing to contribute, determine the extent to which the cost of volumetric-related works can be reduced. Mathematically, R_{rcv} can be written as follows:

$$R_{\mathrm{rcv}} = (R_{\mathrm{v}} \cap S_{\mathrm{v}}) * a + (R_{\mathrm{v}} \cap W_{\mathrm{v}}) * b \quad [\mathrm{m}^3] \tag{4}$$

The first term on the right side of the equation shows the shared volume between road and sewer multiplied by a cost-sharing factor a. The second term similarly shows the shared volume between road and water, multiplied by a factor b. The factors a (sewer coverage for road) and b (water coverage for road) represent the proportion of costs covered by sewer and water for road, respectively. If, for example, $a = 1/2$ and $b = 2/3$, they indicate that sewer covers half of the expenses of the shared trench volume with the road and water covers two-third of the costs of the shared trench with the road. If $a = 0$ and $b = 0$, they indicate that the road operator pays all the costs related to its shared trench volume with sewer and water. These factors are subject to negotiation agreements between the utilities.

Similarly, the reduced cost of volumetric-related work for sewer (S_{rcv}) and water (W_{rcv}) can be written as:

$$S_{\mathrm{rcv}} = (R_{\mathrm{v}} \cap S_{\mathrm{v}}) * c + (S_{\mathrm{v}} \cap W_{\mathrm{v}}) * d \quad [\mathrm{m}^3] \tag{5}$$

$$W_{\mathrm{rcv}} = (R_{\mathrm{v}} \cap W_{\mathrm{v}}) * e + (S_{\mathrm{v}} \cap W_{\mathrm{v}}) * f \quad [\mathrm{m}^3] \tag{6}$$

c denotes the proportion of costs covered by road for sewer (road coverage for sewer). d denotes the proportion of costs covered by water for sewer (water coverage for sewer). e denotes the proportion of costs covered by road for water (road coverage for water). And f denotes the proportion of costs covered by sewer for water.

In the same way, the reduced cost of areal-related work (rca) can be calculated as:

$$R_{\mathrm{rca}} = (R_{\mathrm{a}} \cap S_{\mathrm{a}}) * a + (R_{\mathrm{a}} \cap W_{\mathrm{a}}) * b \quad [\mathrm{m}^2] \tag{7}$$

$$S_{\mathrm{rca}} = (R_{\mathrm{a}} \cap S_{\mathrm{a}}) * c + (S_{\mathrm{a}} \cap W_{\mathrm{a}}) * d \quad [\mathrm{m}^2] \tag{8}$$

$$W_{\mathrm{rca}} = (R_{\mathrm{a}} \cap W_{\mathrm{a}}) * e + (S_{\mathrm{a}} \cap W_{\mathrm{a}}) * f \quad [\mathrm{m}^2] \tag{9}$$

CSP for a utility can be obtained by combining the reduced cost of volumetric-related work and areal-related works, as follows:

$$R_{\mathrm{csp}} = \frac{R_{\mathrm{rca}} * \alpha + R_{\mathrm{rcv}} * \beta}{R_{\mathrm{a}} * \alpha + R_{\mathrm{v}} * \beta} * 100 \quad [\%] \tag{10}$$

$$S_{csp} = \frac{S_{rca}*\alpha + S_{rcv}*\beta}{S_a*\alpha + S_v*\beta}*100 \quad [\%] \tag{11}$$

$$W_{csp} = \frac{W_{rca}*\alpha + W_{rcv}*\beta}{W_a*\alpha + W_v*\beta}*100 \quad [\%] \tag{12}$$

where α and β are the unit costs of surface and volume works, respectively. R_a, R_v, S_a, S_v, W_a, and W_v are the total area or volume of the road, sewer, and water trenches, respectively.

To estimate how much the total costs, irrespective of utility-specific savings, can be reduced (for instance, when considering utilities that are entirely publicly owned), the overall CSP can be calculated. This is achieved by aggregating a weighted average of the individual cost-saving potentials for each utility, as follows:

$$\text{Overall}_{csp} = \frac{R_{csp}*(R_a*\alpha + R_v*\beta) + S_{csp}*(S_a*\alpha + S_v*\beta) + W_{csp}*(W_a*\alpha + W_v*\beta)}{(R_a*\alpha + R_v*\beta) \; + (S_a*\alpha + S_v*\beta) + (W_a*\alpha + W_v*\beta)}*100 \quad [\%] \tag{13}$$

In the case of a typical trench in Norway (300 mm diameter pipe, 2.6 m deep, 1:1 slope, and 0.7 m width at bottom), areal-related work of the trench costs around twice as much as the volumetric-related work, meaning that $\frac{\alpha}{\beta} \sim 2$. The last four equations for a typical Norwegian trench then equal to:

$$R_{csp} = \frac{R_{rca} + 2*R_{rcv}}{R_a + 2*R_v}*100 \quad [\%]$$

$$S_{csp} = \frac{S_{rca} + 2*S_{rcv}}{S_a + 2*S_v}*100 \quad [\%]$$

$$W_{csp} = \frac{W_{rca} + 2*W_{rcv}}{W_a + 2*W_v}*100 \quad [\%]$$

$$\text{Overall}_{csp} = \frac{R_{csp}*(R_a + 2*R_v) + S_{csp}*(S_a + 2*S_v) + W_{csp}*(W_a + 2*W_v)}{(R_a + 2*R_v) \; + (S_a + 2*S_v) + (W_a + 2*W_v)}*100 \quad [\%]$$

To explore the cost-sharing negotiations and its sensitivity on the CSP on a network, five realistic scenarios were developed. In these scenarios, sewer and water utilities equally share the costs for the shared volumetric- and areal-related work between themselves in all scenarios (hence, $d = 1/2$, and $f = 1/2$), but they negotiate with the road utility on sharing the costs of shared work. The scenarios are as follows:

I. Road pays all: the road utility triggers the intervention and bears all the costs associated with the road, including the shared work with the sewer and water utilities. Hence, its cost coverage factors by sewer and water are zero. (i.e., $a = 0$ and $b = 0$). This scenario represents an opportunistic maintenance strategy for the sewer and water utilities, where they wait for the road utility to open the trench and bear the associated costs. Therefore, the sewer and water utilities' cost coverage factors by the road are 100% (i.e., $c = 1$ and $e = 1$) in this scenario.

II. Road's double contribution: the road utility contributes twice as much, compared to sewer and water, for the costs of shared work with them (hence, road coverage for sewer and water is two-third ($c = 2/3$ and $e = 2/3$), sewer and water coverage for the road is one-third ($a = 1/3$, $b = 1/3$). In this scenario, the road utility triggers the intervention, but through negotiation, an agreement is reached for the road to contribute twice the amount for any shared work with sewer and water.

III. Equal contribution: all utilities contribute equally to the costs of the shared works between them ($a = 1/2$, $b = 1/2$, $c = 1/2$, and $e = 1/2$).

IV. Road's half contribution: the road utility contributes half, compared to sewer and water, for the costs of shared works with sewer and water. In this scenario, the sewer and/or water utilities trigger the intervention, but through negotiation, an agreement is reached for road to contribute half the amount, compared to what the sewer and water utilities contribute ($a = 2/3$, $b = 2/3$, $c = 1/3$, $e = 1/3$).

V. Road's null contribution: the road utility contributes nothing for the costs of its shared work with sewer and/or water, as sewer and/or water utilities trigger the intervention, and road simply joins. This scenario represents an opportunistic maintenance strategy for the road ($a = 1$, $b = 1$, $c = 0$, $e = 0$).

Scenarios 2, 3, and 4 indicate possible outcomes for negotiation between the utilities when it is not clear who is the 'opportunistic maintainer'. Nevertheless, these scenarios are made arbitrarily for the purpose of evaluating the sensitivity of different cost-sharing potentials. They do not serve as cost-sharing frameworks.

A summary of the values of the cost-saving factors for each scenario is tabulated in Table 1.

3. RESULTS AND DISCUSSION

The findings pertaining to the co-located surface area and volume of trenches among road, sewer, and water networks in six Norwegian municipalities are presented using radar charts (and tables in Appendices 7.2 and 7.3, available online) and they are organized as follows (the bold abbreviation always points to the variable of comparison):

- The shared trench surface area between the networks in urban and rural areas with three depth scenarios is presented in Figure 6. This is mainly of interest for the road utility as it reflects the extent of surface reconstruction works when replacing the piped networks.
- The shared trench volumes are divided into two figures to maintain clarity and avoid overcrowding. Figure 7 illustrates the shared trench volume between two asset types and between a single asset and the union of the other two. The depth scenarios are also shown.
- Additionally, Figure 8 showcases cost-saving potentials in urban and rural areas using the five defined scenarios of negotiation.
- Figure 9 explores the effect of depth variations on the CSP. For readability, it only includes two extreme negotiation scenarios: Road pays all and road's null contribution.

The computations for intersecting trench volumes over the networks executed by Geometry3D experienced occasional errors, primarily attributable to software glitches within the library. This issue prevented approximately 3–10% of overlap calculations for a whole network from being processed. However, to handle these sporadic issues, an 'except and pass' strategy was employed in the code, allowing the program to bypass these errors and continue processing. It is believed that these errors are indicative of randomly distributed conditions across the entire network. As a result, despite these intermittent processing failures, the findings presented in percentages remain reliable and representative of the networks.

According to the findings shown in Figure 6, surface area co-location follows a similar pattern in all case studies. Water pipes exhibit the highest degree of co-location in terms of trench surface area with sewer trenches compared to any other asset pairs. This trend is particularly evident in urban areas and remains consistent across the municipalities examined. On average across all the municipalities, approximately 60% of the surface area of water trenches ($\boldsymbol{W_a}$) is shared with sewer trenches (S_a) (i.e., $S_a \cap W_a$ $(S_a \cap W_a)/W_a = 60\%$). It should be noted that sewer includes the union of sewage and stormwater, which means the sewer trenches are quite big compared to the water trenches. Consequently, when calculating the shared trench surface area of the water mains with sewer pipes (i.e., $S_a \cap \boldsymbol{W_a} = (S_a \cap W_a)/W_a$), the resulting degree of surface co-location for water tends to be higher, while the resulting degree of co-location for sewer tends to be lower.

Table 1 | Multipliers of shared trench volume/area under different scenarios

Scenarios		a	b	c	d	E	f
I	Road pays all	0	0	1	1/2	1	1/2
II	Road's double contribution	1/3	1/3	2/3	1/2	2/3	1/2
III	Equal contribution	1/2	1/2	1/2	1/2	½	1/2
IV	Road's half contribution	2/3	2/3	1/3	1/2	1/3	1/2
V	Road's null contribution	1	1	0	1/2	0	1/2

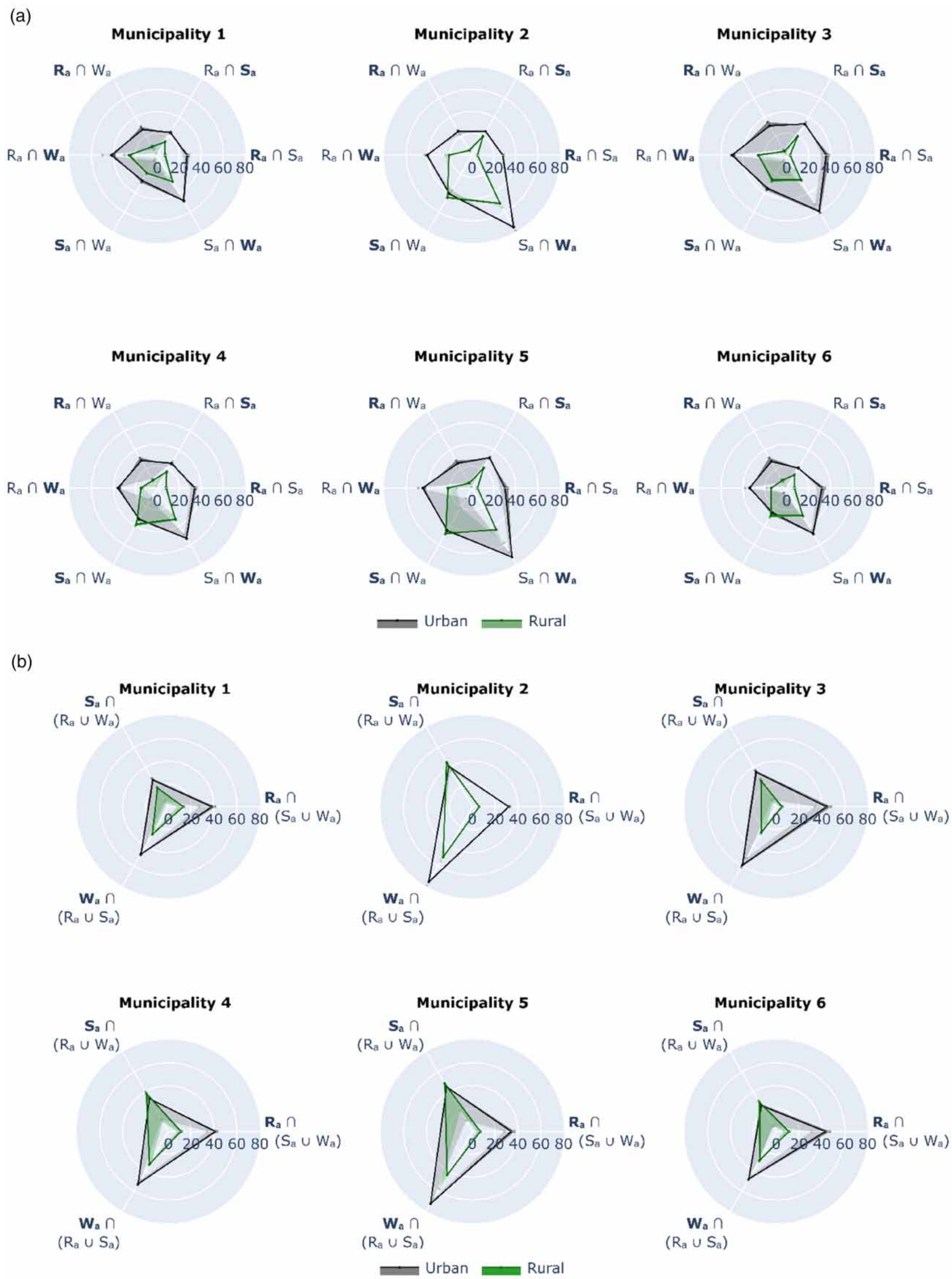

Figure 6 | Shared area between assets as a percentage of bolded assets. (a) Between each pair of assets and (b) between an asset and the union of the other two. The fully opaque lines show shared areas where the missing depths were imputed with the average depth, while areas filled with darker and lighter colors show shared areas where the missing depths were imputed with maximum and minimum depths recommended by Norsk Vann (2004), respectively.

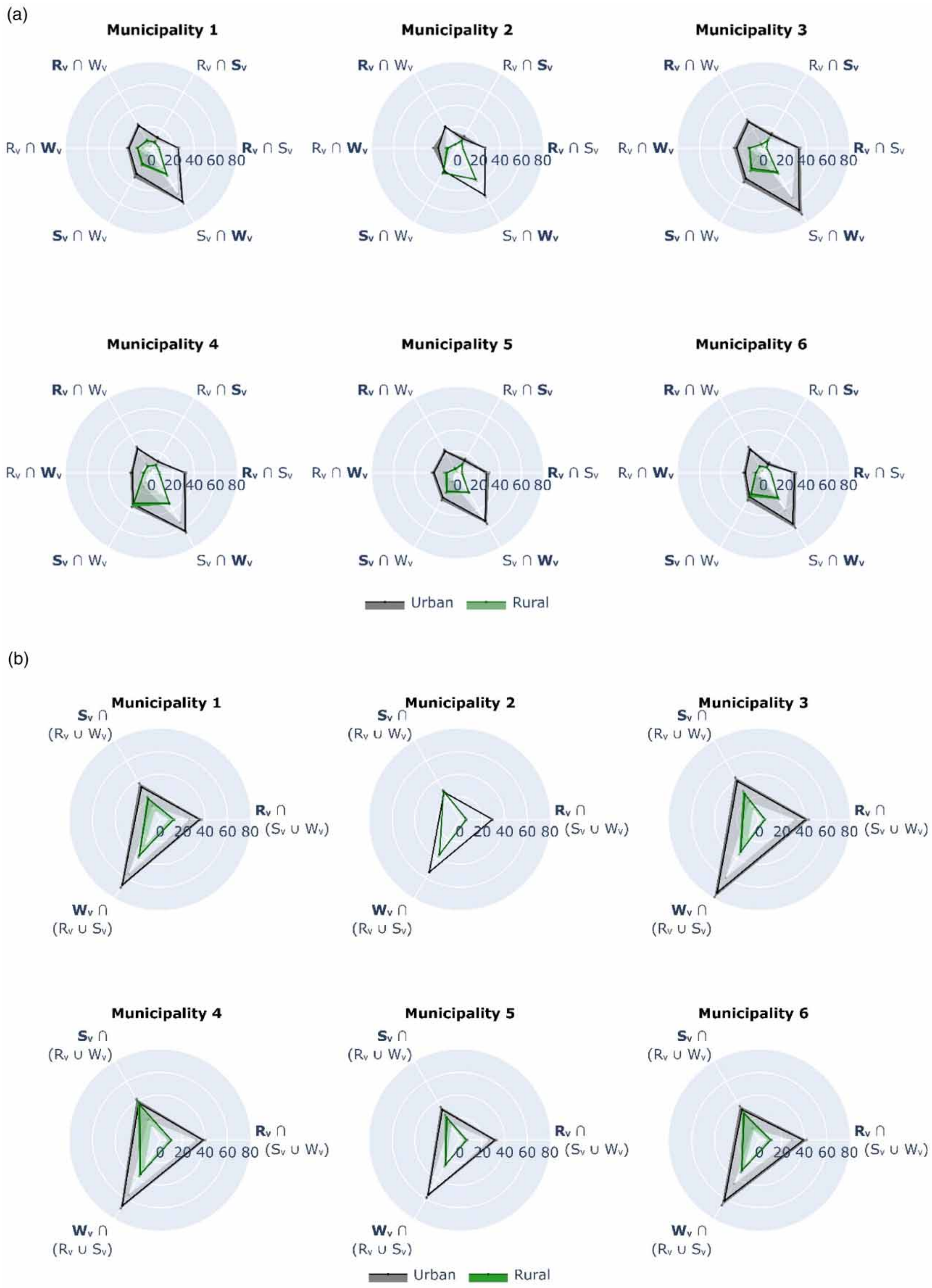

Figure 7 | Shared volume between assets as a percentage of bolded assets. (a) Between each pair of assets and (b) between an asset and the union of the other two. The fully opaque lines show shared volumes where the missing depths were imputed with the average depth, while areas filled with darker and lighter colors show shared areas where the missing depths were imputed with maximum and minimum depths recommended by Norsk Vann (2004), respectively.

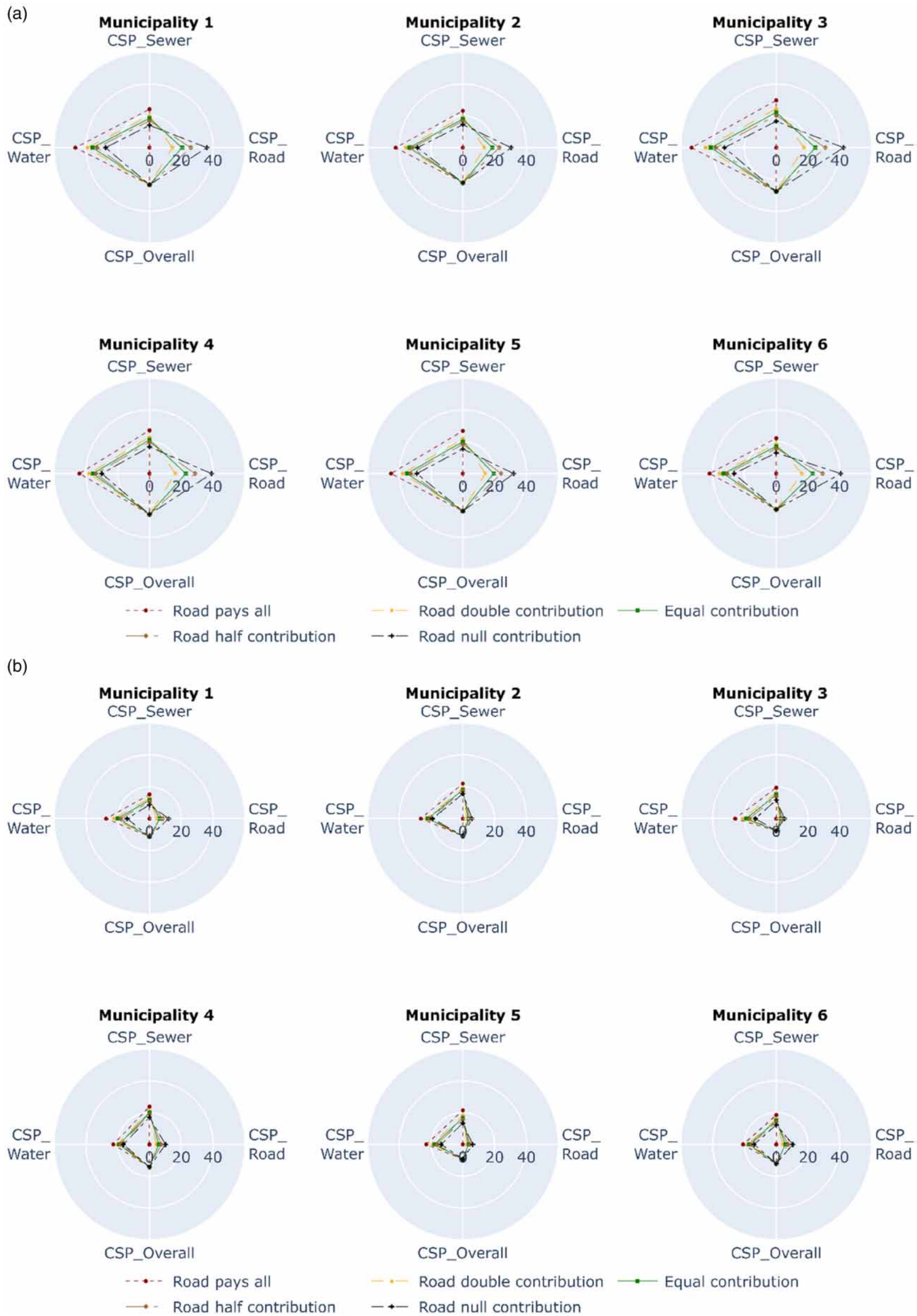

Figure 8 | Cost-saving potential of IMAM (a) in urban areas and (b) in rural areas.

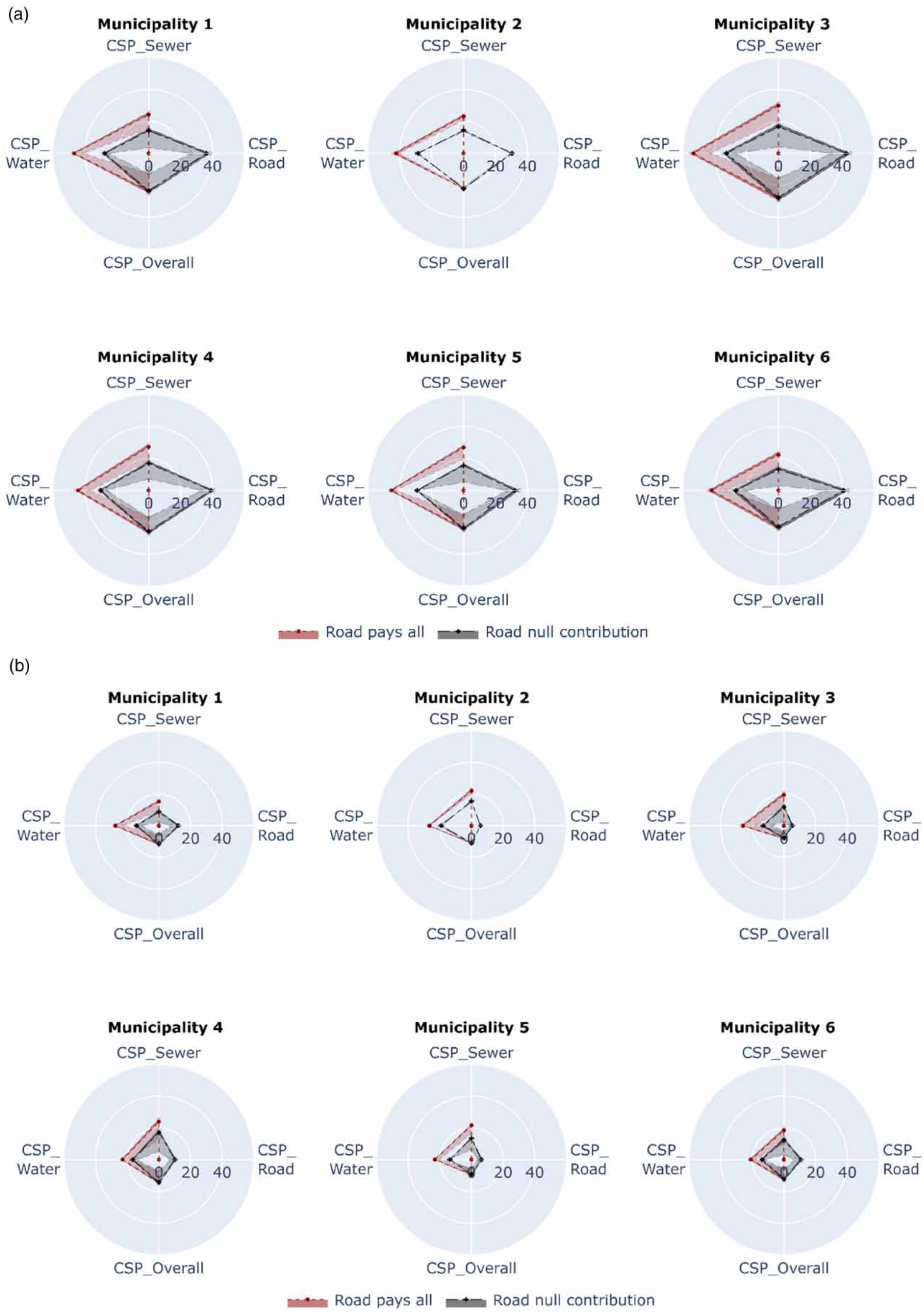

Figure 9 | Variation of CSP in (a) urban areas and (b) rural areas with regard to the depth of trenches. The fully opaque lines show CSP where the missing depths were imputed with the average depth, while areas filled with darker and lighter colors show CSP where the missing depths were imputed with maximum and minimum depths recommended by Norsk Vann (2004), respectively.

Approximately 36% of the surface area of sewer trenches ($\boldsymbol{S}_{\mathbf{a}}$) is shared with water trenches (W_a) (i.e., $\boldsymbol{S}_{\boldsymbol{a}} \cap W_a = (S_a \cap W_a)/S_a = 36\%$).

In contrast, road surfaces (R_a) demonstrate a lower degree of co-location with both sewer and water trenches. Approximately 33% of the total road surface is shared with the sewer trench surface, while around 30% of the road surface is shared with the water trench surface. However, when the sewer and water trenches are combined, the co-location with the road surface increases to approximately 42% (i.e., $\boldsymbol{R}_{\mathbf{a}} \cap (W_a \cup S_a)$). These numbers are in line with the findings of (Mair *et al.* (2017) that 50% of the street network contains 78% of the water supply or sewer network.

Moreover, in rural areas, particularly interesting is that the results show a higher percentage of the shared surface area of the sewer with water trenches, sometimes even higher than in urban areas, which might be misleading. Since more decentralized solutions exist for sewer systems, resulting in fewer sewer pipes and hence, fewer sewer trenches which eventually translate to less total surface area (and also volume) for sewer trenches, and putting the total surface area of sewer trenches in the denominator (i.e., $(S_a \cap W_a)/S_a$) results in higher values for the percentage of shared surface area of sewer with water trenches.

The variations in shared areas with regard to changes in pipe depth mainly depend on how the depth affects the trench shapes. The shared areas are less affected when the depth is changed from average to maximum, while they are most affected when the minimum depth is considered. This is due to the trench shapes: with average and maximum pipe depths, trench shapes are trapezoidal prisms, while with minimum pipe depths, the trenches are mostly less than 2 m depth and therefore, their shapes change to rectangular prisms, heavily affecting the trench surface area. In Municipality 2, where missing depths are minimal, the shared area variations are also minimal.

Regarding the shared volumes in Figure 7, the patterns also remain consistent across all the case studies. Water pipes consistently demonstrate the highest degree of co-location with sewer trenches compared to any other asset pairs (Figure 7(a)). In urban areas, water pipes share 51–67% (60% on average) of their trench volumes with sewer trenches, while in rural areas, these values are around half compared to urban areas. On the other hand, from the perspective of sewer pipes, lower percentages of shared volume with water trenches are observed (25–36%, 30% on average), mainly due to the unionization of sewage and stormwater trenches. In urban areas, the average shared volume across the municipalities is around 30%, which is almost half of the shared volume of water pipes with sewer trenches. Roads share around 25% of their trench volumes with water and 30% with sewer trenches. The variation of their average shared volume across the municipalities is minimal.

The higher degree of co-location between sewer and water pipes, although beneficial for rehabilitation purposes, poses a significant risk of contamination to drinking water systems. In instances of low or negative pressure in drinking water systems, due to factors such as pipe breaks or pump failures, co-located leaky sewer systems can contaminate the drinking water (Besner *et al.* 2011). Studies, such as those conducted in England (Hunter *et al.* 2005) and Norway (Nygard *et al.* 2007), have demonstrated clear correlations between water pressure loss and waterborne diseases. However, it is not clear whether the presence of leaky sewer pipes increases the risk of contamination, as sewer pipes are not the sole source of contamination in underground.

It is worth noting that in rural areas, the proportion of sewer trenches shared with water trenches (ranging from 18 to 38%) can be higher than in urban areas due to the same reasons mentioned earlier for the area co-location. However, the dynamics differ for roads. In rural areas, there are more roads compared to pipe networks, especially compared to sewer pipes. Consequently, the shared volume of the road networks with the pipe networks decreases considerably.

In Figure 7(b), the degree of shared volumes between an asset and the union of the other two assets is depicted. When sewer trenches are combined with road trenches, the shared volume of water trenches with this combination increases to between 54 and 75% in urban areas, and in rural areas, it rises to between 25 and 38%. On average, this represents a 4% increase compared to the shared volume of water trench with only sewer trench. This indicates that including the road utility in the intervention does not significantly increase the shared volume of water. However, it can lead to substantial cost savings since the cost of shared volume can be shared with both sewer and road utilities instead of sharing with just the sewer utility. Regarding the depth scenarios, similar trends can be observed in shared volumes as in shared areas.

When translating the shared volumes and areas into a proxy for CSP (see Figure 8), it becomes evident that depending on the utility, a considerable amount of costs can be shared and hence saved. The CSP from the five scenarios is presented where the road utility's range of cost saving in an urban area is between 0 and 42%, meaning that the road utility can save up to 42% if it practices opportunistic maintenance. For the water and sewer utilities, the maximum savings can be up to 53 and 30%, respectively, if these two utilities practice opportunistic maintenance. However, CSP for sewer and water in scenario V (when the road utility contributes nothing for the shared work) is not reduced overwhelmingly, as it did for roads in scenario I. The reason is that in scenario V sewer and water are still considered to equally share the cost of the shared work between themselves, which can save costs significantly due to their higher degree of co-location. In the equal contribution scenario (III), road, sewer, and water on average can save 21, 20, and 36%, respectively.

In rural areas (as shown in Figure 8(b)), the CSP of IMAM is generally around half of that in urban areas, except for roads where the potential is almost negligible, typically less than 10%. This is primarily due to the presence of numerous roads in rural areas without nearby piped infrastructures. The lower potential for cost-saving combined with the uncertainties in the data and model accuracy can make IMAM practices less attractive in rural areas.

Irrespective of utility-specific savings and negotiations, the overall CSP, when all three infrastructures can join interventions, on average is around 24% in urban settings and around 11% in rural settings. Existing cost estimations are scarce, but the results of the available ones are in line with our findings. In their study, Kleiner *et al.* (2010) assumed these savings to be around 20% for water supply networks when coordinated with road networks, while Burger & Hochedlinger (2008) suggest that even 25% could be saved. Calculations by Tscheikner-Gratl (2016), using a standard cross-section, showed an overall average saving of 15.6%. Moreover, modeling the effects of integrated rehabilitation on road, sewer, and water networks' long-term sustainability, Pericault *et al.* (2023) quantified the cost and carbon reductions of IMAM. Their findings revealed that by implementing coordination windows of 35 and 25 years, cost reductions of 34% and greenhouse gas emissions reductions of 16% could be achieved. Notably, their projected cost savings exceed our estimates.

Even though most infrastructures are publicly owned, determining the savings allocation often becomes a matter of negotiation. Nevertheless, the metrics proposed for quantifying the spatial relations between the infrastructures can serve as a useful information basis for such negotiations.

The effect of depth variations on CSP is illustrated in Figure 9. With two cost negotiation scenarios (road pays all and road's null contribution), maximum and minimum cost savings with respect to different depths can be observed. While the overall average cost savings in urban areas is around 24%, it can vary from 14 to 29%, depending on the depth scenarios. The CSP for sewers can be heavily affected by the depth variations. In certain cases (Municipality 3 and road's null contribution), the CSP for sewers is as low as 3%. The CSP of roads is moderately affected, while that of water is minimally affected. The CSP for water can be as high as 56%. Not surprisingly, the variations of CSP for Municipality 2 are minimal as the missing depth data is minimal. For rural areas, with variations in depth, the CSP for roads is negligible with the minimum depth scenario. However, water can achieve savings of up to 27% in certain conditions.

4. LIMITATIONS

The potential savings estimated in this study only include the reduced costs of integrated interventions that avoid repeated excavation and resurfacing works. However, they do not account for other benefits such as shorter construction periods (which reduce the economic impact on local businesses unable to operate during construction), fewer traffic detours, or the environmental advantages of lowering carbon dioxide emissions. Quantifying these additional benefits is reserved for future research.

On the other hand, there can also be extra costs associated with the coordination itself that the utilities may incur (e.g., establishing a coordination committee or system development aimed at fostering seamless coordination) when performing integrated interventions. The cost of coordination may vary from case to case and depend, at least, on the utilities' structural organizations, available technologies that connect them, the level of coordination (Daulat *et al.* 2022), and the site-specific logistical and practical challenges associated with integrated interventions. Assessment of net cost saving is important for the uptake of IMAM and necessary for strategic decisions. Such an assessment merits further research. However, problems with data unavailability can be mainly hindering the research.

The five scenarios for CSP evaluated in this study range from the maximum to minimum savings of the utilities, providing an overview of the sensitivity of different negotiation agreements with the overall cost-sharing potential of the utilities. As a future direction, it would be intriguing to integrate serious gaming theories for IMAM (e.g., van Riel *et al.* 2017b) into the CSP model to simulate utility negotiations and their impact on CSP outcomes. Additionally, the CSP model can also be applied in game theory to model stakeholder preferences, costs, and action payoffs. This approach can facilitate negotiations among stakeholders, allowing them to reach mutually beneficial agreements for IMAM. It is important to note that several methods, ranging from serious games like 'Maintenance in Motion' (van Riel *et al.* 2017b) to the involvement of various stakeholder groups through multicriteria decision-making (Tscheikner-Gratl *et al.* 2017a), are offered by the literature to include negotiations and stakeholder preferences into the IMAM.

It is important to note that this study evaluated the maximum potential on a network scale, assuming that IMAM is always feasible. To include different deterioration rates of the assets and convert the strategic level (network level) information to a tactical level (project level), a risk-based approach would be necessary. The introduced metrics could be used to estimate savings at the project level too; however, highly accurate data would be required to do so. Due to variations in spatiotemporal degrees and a general inclination for integrating public works, the participating decision-makers need to agree on if, where, and when they will work together (van Riel *et al.* 2017a).

While the financial benefits might differ across networks, distributing the savings can be challenging, especially if some infrastructures count on the possibility of opportunistic maintenance, or have more leeway due to their longer life expectancy. In a related study, Nguyen *et al.* (2022) conducted a quantitative analysis of maintenance and user cost savings resulting from various interventions applied to roads and water pipes. They integrated these findings with asset deterioration models. By simulating different deterioration scenarios, they were able to ascertain the potential cost savings generated by joint maintenance efforts in a synthetic project context. The key insight from their research reveals that the greatest cost savings tend to be realized when both assets – the road and the water pipe – are concurrently in poor condition. It is also important to note that the participation of other co-located networks, e.g., electricity and data cables might alter the CSP outcomes.

Furthermore, the case studies used in this study are representative of small to medium-sized municipalities with similar standards of construction as Norway, and the numbers may or may not hold true for more densely urbanized areas or areas where the local codes of practice differ considerably in regard to the construction and renovation practices in Norway. Considering the pattern between urbanization and co-location, it is possible that the potential is underestimated, as higher urbanization often leads to a higher degree of co-location, as well as higher unit costs of infrastructure rehabilitation. However, it is important to acknowledge that specific design choices may strongly affect the degree of co-location, i.e., positioning drinking water underneath sidewalks, or simply having very wide roads, can lower the degree of co-location. Moreover, a lower degree of co-location can lead to silo-based interventions and partial replacement of roads, resulting in lower quality roads (Torbaghan *et al.* 2020). Utilities might find it beneficial to either cluster their assets closely together (high degree of co-location) or keep them distinctly separated (zero degree of co-location).

Last but not least, the reliability of results depends on the accuracy of the geolocation data of the assets. The accuracy of the horizontal location of underground water pipes can vary depending on several factors, including the age of the infrastructure, the technology used for mapping and locating the pipes, and the records kept by the utilities over time. Given that these types of data have been collected over many years (Wang & Yin 2022), measuring or verifying the accuracy of the data is not feasible for this study. Consequently, this limitation prevents an uncertainty analysis of the degree of co-location and the CSP due to horizontal location discrepancies.

5. CONCLUSION

Infrastructure networks are not completely co-located. Knowing the degree of geographic co-location can provide valuable insights and aid in strategic planning. This study focused on assessing the degree of co-location and its application on the CSP of water, sewer, and road networks in six Norwegian municipalities. Two metrics, shared surface area and volume of open-cut trenches were utilized to quantify the degree of co-location. The findings revealed variations in shared surface area and volume between the different infrastructure types, particularly in urban and rural areas. These findings provide valuable information for decision-making and highlight the potential benefits of coordinated infrastructure management.

Among the networks, water networks exhibited the highest degree of co-location with sewer networks, followed by road networks. In rural areas, the proportion of shared surface area and volume of sewer trenches with water trenches can be even higher than in urban areas due to decentralized sewer systems and fewer sewer pipes. Furthermore, the co-location with roads decreases considerably in rural settings. The CSP of water and sewer networks is generally around half in rural areas compared to urban areas, while for roads the potential is minimal. These findings underpin the importance of understanding the degree of co-location for effective infrastructure management.

The key findings of this work are as follows:

- In urban areas, on average (i.e., network level):
  - Water pipe trenches share 60% of its trench volume and 60% of their trench surface area with sewer and road trenches.

  - ○ The shared volume of sewer trenches with water trenches is around half of that.
  - ○ Road utilities share 25% of their trench volume with water and 30% with sewer trenches. Its variation across the municipalities is minimal.
  - ○ In the best-case scenarios of each utility, the CSP of integrated interventions are 42, 30, and 53%, for road, sewer, and water utilities, respectively.
- The overall CSP of integrated interventions in urban areas is around 24%. This potential in rural areas is around half (11%).
- Missing depth data can affect the estimation of the degree of co-location and CSP, depending on the amount of missing data and the utility for which the estimation is made. In the worst-case scenario, the results show an overall CSP of 14%.

While the findings of this study provide valuable insights into the co-location patterns and benefits of integrated interventions of water, sewer, and road networks in small to medium-sized municipalities, it is important to acknowledge the limitations of the case studies. The highlighted cost-saving potentials might not be indicative of densely urbanized regions. In such areas, the opportunity for cost savings might be even greater due to the potential higher degree of co-location. Future studies should therefore use the highlighted methodology on cases with a high variety of size, layout, level of urbanization, and standards and codes of practice to draw a more complete picture of the shown potential. Additionally, the presented cost savings are on a network level and based on the assumption that all infrastructures can be renewed simultaneously. Future research should focus on linking the degree of co-location with deterioration models to assess actual savings. Because some assets may be co-located (spatially close), but due to different times of failures (temporally distant), they might not be suitable for integrated interventions. By considering both spatial and temporal variations, a more accurate estimation of cost savings and effective utilization of integrated management can be achieved. It is worth noting that coordination between infrastructure utilities can be challenging due to different priorities and budgeting limitations. IMAM shows promise in utilizing synergies, but its feasibility should be assessed by weighing the benefits of co-location against implementation costs and obstacles.

ACKNOWLEDGMENT

We extend our sincere thanks to Professors Francois H.L.R Clemens-Meyer, and Alex Klein-Paste for their feedback and discussions. Our gratitude also goes to Spyridon Pritsis, Bulat Kerimov, and Mahdi Bahrami for their insightful comments and discussions during the analysis. Their collective expertise has greatly enriched this manuscript.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abu Samra, S., Ahmed, M., Hammad, A. & Zayed, T. 2018 Multiobjective framework for managing municipal integrated infrastructure. *Journal of Construction Engineering and Management* **144** (1), 04017091. https://doi.org/10.1061/(asce)co.1943-7862.0001402.

Abu-Samra, S., Ahmed, M. & Amador, L. 2020 Asset management framework for integrated municipal infrastructure. *Journal of Infrastructure Systems* **26** (4), 04020039. https://doi.org/10.1061/(asce)is.1943-555x.0000580.

Araya, F. & Vasquez, S. 2022 Challenges, drivers, and benefits to integrated infrastructure management of water, wastewater, stormwater and transportation systems. *Sustainable Cities and Society* **82**, 103913. https://doi.org/10.1016/j.scs.2022.103913.

Besner, M.-C., Prévost, M. & Regli, S. 2011 Assessing the public health risk of microbial intrusion events in distribution systems: Conceptual model, available data, and challenges. *Water Research* **45** (3), 961–979. https://doi.org/10.1016/j.watres.2010.10.035.

Burger, G. & Hochedlinger, M. 2008 Festlegung von Sanierungsprogrammen – Vor- und Nachteile einer Baustellenkoordination anhand von Beispielen. In H. Kainz (Ed.), *Instandhaltung von Trinkwasser- und Abwasserleitungen*. Technische Universität Graz, 54, Verlag der Technischen Universität Graz.

Carey, B. D. & Lueke, J. S. 2013 Optimized holistic municipal right-of-way capital improvement planning. *Canadian Journal of Civil Engineering* **40** (12), 1244–1251. https://doi.org/10.1139/cjce-2012-0183.

Daulat, S., Rokstad, M. M., Klein-Paste, A., Langeveld, J. & Tscheikner-Gratl, F. 2022 Challenges of integrated multi-infrastructure asset management: A review of pavement, sewer, and water distribution networks. *Structure and Infrastructure Engineering* **20** (4), 546–565. https://doi.org/10.1080/15732479.2022.2119480.

Directorate-General for Environment 2022 Proposal for a Directive of the European Parliament and of the Council Concerning urban wastewater treatment (recast). European Commission. Available from: https://environment.ec.europa.eu/document/download/a936c2d5-2e3a-4eb1-a7c6-41ec98f3e72f_en?filename=Proposal%20for%20a%20Directive%20concerning%20urban%20wastewater%20treatment%20%28recast%29.pdf.

European Commission 1991 Urban waste water treatment directive. *Official Journal of the European Communities L 135/40*.

European Commission 2020 DIRECTIVE (EU) 2020/2184-Drinking Water Directive. European Commission.

Eurostat 2021 *Applying the Degree of Urbanisation – A Methodological Manual to Define Cities, Towns and Rural Areas for International Comparisons*. Publications office of the European Union, Luxembourg.

GeoNorge 2019 *Befolkning på rutenett 1000 m [Population on 1000 m cells]*. Kartkatalogen. Available from: https://kartkatalog.geonorge.no/metadata?text=Befolkning%20p%C3%A5%20rutenett%201000%20m%202019.

Gou, M. 2021 *Geometry3D: 3D Computational Geometrics Library [Software]*. Available from: https://github.com/GouMinghao/Geometry3D.

Halfawy, M. R. 2010 Municipal information models and federated software architecture for implementing integrated infrastructure management environments. *Automation in Construction* **19** (4), 433–446. https://doi.org/10.1016/j.autcon.2009.11.013.

Huang, Y. H. 2004 *Pavement Analysis and Design*, 2nd edn.. Pearson Prentice Hall, Upper Saddle River, NJ, USA.

Hunt, D. V. L., Nash, D. & Rogers, C. D. F. 2014 Sustainable utility placement via multi-utility tunnels. *Tunnelling and Underground Space Technology* **39**, 15–26. https://doi.org/10.1016/j.tust.2012.02.001.

Hunter, P. R., Chalmers, R. M., Hughes, S. & Syed, Q. 2005 Self-reported diarrhea in a control group: A strong association with reporting of low-pressure events in tap water. *Clinical Infectious Diseases* **40** (4), e32–e34. https://doi.org/10.1086/427750.

InfraGuide 2005 *Managing Infrastructure Assets. Federation of Canadian Municipalities and National Research Council*. Available from: https://fcm.ca/sites/default/files/documents/resources/guide/infraguide-managing-infrastructure-assets-mamp.pdf.

Islam, T. & Moselhi, O. 2012 Modeling geospatial interdependence for integrated municipal infrastructure. *Journal of Infrastructure Systems* **18** (2), 68–74. https://doi.org/10.1061/(asce)is.1943-555x.0000065.

Jayasinghe, P. A., Derrible, S. & Kattan, L. 2023 Interdependencies between urban transport, water, and solid waste infrastructure systems. *Infrastructures* **8** (4), Article 4. https://doi.org/10.3390/infrastructures8040076.

Jordahl, K., Van den Bossche, J., Fleischmann, M., Wasserman, J., McBride, J., Gerard, J., Tratner, J., Perry, M., Badaracco, A. G., Farmer, C., Hjelle, G. A., Snow, A. D., Cochran, M., Gillies, S., Culbertson, L., Bartos, M., Eubank, N., maxalbert, Bilogur, A., Rey, S., Ren, C., Arribas-Bel, D., Wasser, L., Wolf, L. J., Journois, M., Wilson, J., Greenhall, A., Holdgraf, C., Filipe, & Leblanc, F. 2023 *geopandas/geopandas: V0.13.0* [Computer software]. https://doi.org/10.5281/ZENODO.7902652.

Jung, Y. J. & Sinha, S. K. 2007 Evaluation of trenchless technology methods for municipal infrastructure system. *Journal of Infrastructure Systems* **13** (2), 144–156. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:2(144).

Kammouh, O., Nogal, M., Binnekamp, R. & Wolfert, A. R. M. R. 2021 Multi-system intervention optimization for interdependent infrastructure. *Automation in Construction* **127** (March), 103698. https://doi.org/10.1016/j.autcon.2021.103698.

Kerwin, S. & Adey, B. T. 2020 Optimal intervention planning: A bottom-up approach to renewing aging water infrastructure. *Journal of Water Resources Planning and Management* **146** (7), 04020044. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001217.

Kielhauser, C. 2018 *A Method for Determining Optimal Intervention Programs for Interrelated Infrastructure Networks. Doctoral Dissertation*, ETH Zurich. https://doi.org/10.3929/ethz-b-000269313.

Kielhauser, C. & Adey, B. T. 2020 Determination of intervention programs for multiple municipal infrastructure networks: Considering network operator and service costs. *Sustainable and Resilient Infrastructure* **5** (1–2), 49–61. https://doi.org/10.1080/23789689.2018.1497879.

Kleiner, Y., Nafi, A. & Rajani, B. 2010 Planning renewal of water mains while considering deterioration, economies of scale and adjacent infrastructure. *Water Science and Technology: Water Supply* **10** (6), 897–906. https://doi.org/10.2166/ws.2010.571.

Le Gat, Y., Curt, C., Werey, C., Caillaud, K., Rulleau, B. & Taillandier, F. 2023 Water infrastructure asset management: State of the art and emerging research themes. *Structure and Infrastructure Engineering* **0** (0), 1–24. https://doi.org/10.1080/15732479.2023.2222030.

Li, F., Ma, L., Sun, Y. & Mathew, J. 2016 Optimized group replacement scheduling for water pipeline network. *Journal of Water Resources Planning and Management* **142** (1), 04015035. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000559.

Luo, Y., Alaghbandrad, A., Genger, T. K. & Hammad, A. 2020 History and recent development of multi-purpose utility tunnels. *Tunnelling and Underground Space Technology* **103**, 103511. https://doi.org/10.1016/j.tust.2020.103511.

Mair, M., Zischg, J., Rauch, W. & Sitzenfrei, R. 2017 Where to find water pipes and sewers? On the correlation of infrastructure networks in the urban environment. *Water (Switzerland)* **9** (2). https://doi.org/10.3390/w9020146.

Marzouk, M. & Osama, A. 2017 Fuzzy-based methodology for integrated infrastructure asset management. *International Journal of Computational Intelligence Systems* **10** (1), 745–759. https://doi.org/10.2991/ijcis.2017.10.1.50.

Metayer, G., Torres-Machi, C. & Bastias, A. 2020 A proposed framework for the integrated management of municipal infrastructure. *Construction Research Congress* **2020**, 846–855. https://doi.org/10.1061/9780784482865%0Ahttps://trid.trb.org/view/1760497.

Nafi, A. & Kleiner, Y. 2010 Scheduling renewal of water pipes while considering adjacency of infrastructure works and economies of scale. *Journal of Water Resources Planning and Management* **136** (5), 519–530. https://doi.org/10.1061/(asce)wr.1943-5452.0000062.

Nguyen, H., Abdel-Mottaleb, N., Uddin, S., Zhang, Q., Lu, Q., Zhang, H. & Li, M. 2022 Joint maintenance planning of deteriorating co-located road and water infrastructures with interdependencies. *Reliability Engineering & System Safety* **226**, 108678. https://doi.org/10.1016/j.ress.2022.108678.

Nieuwenhuis, E., Cuppen, E., Langeveld, J. & De Bruijn, H. 2021 Towards the integrated management of urban water systems: Conceptualizing integration and its uncertainties. *Journal of Cleaner Production* **280**, 124977. https://doi.org/10.1016/j.jclepro.2020.124977.

Norsk Vann 2004 *Grøfter og ledninger utførelse [Execution of trenches and pipelines]*. VA-Norm. Available from: https://va-norm.no/dokument/4-grofter-og-ledn-utforelse/.

Nygard, K., Wahl, E., Krogh, T., Tveit, O. A., Bohleng, E., Tverdal, A. & Aavitsland, P. 2007 Breaks and maintenance work in the water distribution systems and gastrointestinal illness: A cohort study. *International Journal of Epidemiology* **36** (4), 873–880. https://doi.org/10.1093/ije/dym029.

OECD 2020 Financing water supply, sanitation and flood protection: Challenges in EU member states and policy options. In: *OECD Studies on Water*. OECD Publishing. https://doi.org/10.1787/6893cdac-en.

Osman, H. 2016 Coordination of urban infrastructure reconstruction projects. *Structure and Infrastructure Engineering* **12** (1), 108–121. https://doi.org/10.1080/15732479.2014.995677.

Ottenhoff, E. C. & Korving, H. 2007 Verification tool for sewer database quality. *Water Practice and Technology* **2** (2), wpt2007030. https://doi.org/10.2166/wpt.2007.030.

Pericault, Y., Viklander, M. & Hedström, A. 2023 Modelling the long-term sustainability impacts of coordination policies for urban infrastructure rehabilitation. *Water Research* **236**, 119912. https://doi.org/10.1016/j.watres.2023.119912.

Rokstad, M. M. & Ugarelli, R. M. 2015 Minimising the total cost of renewal and risk of water infrastructure assets by grouping renewal interventions. *Reliability Engineering and System Safety* **142**, 148–160. https://doi.org/10.1016/j.ress.2015.05.014.

Roshani, E. & Filion, Y. R. 2014 Event-Based approach to optimize the timing of water main rehabilitation with asset management strategies. *Journal of Water Resources Planning and Management* **140** (6), 04014004. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000392.

Saidi, S., Kattan, L., Jayasinghe, P., Hettiaratchi, P. & Taron, J. 2018 Integrated infrastructure systems – a review. *Sustainable Cities and Society* **36**, 1–11. https://doi.org/10.1016/j.scs.2017.09.022.

Selvaggio, P., Freni, F., Rossi, R., Di Giorgio, D. C. & Colombo, I. 2018 New generation integrated asset modelling: High-resolution reservoir multi models coupled with an external steady-State network solver. In: *Abu Dhabi International Petroleum Exhibition & Conference*. https://doi.org/10.2118/192603-MS.

Shahata, K., El-Zahab, S., Zayed, T. & Alfalah, G. 2022 Rehabilitation of municipal infrastructure using risk-based performance. *Automation in Construction* **140**, 104335. https://doi.org/10.1016/j.autcon.2022.104335.

Statens Vegvesen 2022 *N200 Vegbygging (N200:2022)*. Statens Vegvesen. Available from: https://viewers.vegnorm.vegvesen.no/product/859942/nb.

Taaveniku, M., Halvarsson, M., Muhammed, A. D., Hopfensitz, M. & Spitzer, H. 2019 *Integrated Asset Management' for Transmission and Distribution Networks at Vattenfall*.

Torbaghan, E. M., Curioni, G., Hayati, F., Royal, A. C., Chapman, D. N., Atkins, P. R. & Rogers, C. D. 2020 Investigating the relationship between trenching practice and road deterioration. *Infrastructure Asset Management* **7** (4), 282–296. https://doi.org/10.1680/jinam.19.00052.

Tscheikner-Gratl, F. 2016 *Integrated Approach for Multi-Utility Rehabilitation Planning of Urban Water Infrastructure: Focus on Small and Medium Sized Municipalities*. *Doctoral Dissertation*, University of Innsbruck.

Tscheikner-Gratl, F., Sitzenfrei, R., Rauch, W. & Kleidorfer, M. 2016 Integrated rehabilitation planning of urban infrastructure systems using a street section priority model. *Urban Water Journal* **13** (1), 28–40. https://doi.org/10.1080/1573062X.2015.1057174.

Tscheikner-Gratl, F., Egger, P., Rauch, W. & Kleidorfer, M. 2017a Comparison of multi-criteria decision support methods for integrated rehabilitation prioritization. *Water (Switzerland)* **9**, 2. https://doi.org/10.3390/w9020068.

Tscheikner-Gratl, F., Mair, M., Rauch, W., Langeveld, J. & Kleidorfer, M. 2017b On the potential of integrated multi-utility asset management in urban water management. In Ugarelli, R., & Sægrov, S. (Eds.), LESAM 2017. IWA Publishing. Trondheim, Norway.

Tscheikner-Gratl, F., Caradot, N., Cherqui, F., Leitão, J. P., Ahmadi, M., Langeveld, J. G., Le Gat, Y., Scholten, L., Roghani, B., Rodríguez, J. P., Lepot, M., Stegeman, B., Heinrichsen, A., Kropp, I., Kerres, K., Almeida, M. do C., Bach, P. M., Moy de Vitry, M., Marques, A. S., Simões, N. E., Rouault, P., Hernandez, N., Torres, A., Werey, C., Rulleau, B. & Clemens, F. 2019 Sewer asset management – state of the art and research needs. *Urban Water Journal* **16** (9), 662–675. https://doi.org/10.1080/1573062X.2020.1713382.

van Riel, W., Langeveld, J., Herder, P. & Clemens, F. 2017a The influence of information quality on decision-making for networked infrastructure management. *Structure and Infrastructure Engineering* **13** (6), 696–708. https://doi.org/10.1080/15732479.2016.1187633.

van Riel, W., Post, J., Langeveld, J., Herder, P. & Clemens, F. 2017b A gaming approach to networked infrastructure management. *Structure and Infrastructure Engineering* **13** (7), 855–868. https://doi.org/10.1080/15732479.2016.1212902.

Wang, M. & Yin, X. 2022 Construction and maintenance of urban underground infrastructure with digital technologies. *Automation in Construction* **141**, 104464. https://doi.org/10.1016/j.autcon.2022.104464.

Zischg, J. 2018 *Understanding Patterns, Dependencies and Resilience in Complex Urban Water Infrastructure Networks*. Austrian Marshall Plan Foundation. Available from: https://www.marshallplan.at/images/All-Papers/MP-2017/Zischg+Jonatan_782.pdf.

First received 4 February 2024; accepted in revised form 29 May 2024. Available online 8 June 2024