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Intensifying rehabilitation of combined sewer systems using trenchless technology in combination with low impact development and green infrastructure

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ABSTRACT

Throughout Europe, there is a considerable need for investment in the upgrade of sewer systems – due to three main factors: ageing infrastructure, climate change and urban population growth. The need for investments is expected to grow significantly in the years ahead. Trenchless rehabilitation (no-dig) of sewer pipelines is a cost-efficient and environmental friendly method for upgrading existing pipelines with sufficient capacity. This study examines the possibility of applying no-dig to combined sewer systems (CS) with insufficient capacity. In this study, a concept assessment methodology that combines the analytical approaches from stormwater and sewer system assessments is presented. The methodology was tested on a case area that was part of an environmental project in Oslo, Norway. Three alternative concepts were examined; A0: no-dig and low impact development (LID), A1: no-dig, LID and green infrastructure (GI), and A2: CS up-sizing using open-cut methods. The study concludes that CS with insufficient capacity can be rehabilitated using no-dig if LID and GI. The combination of no-dig and LID reduces costs considerably but does involve the risk of damages from uncontrolled surface runoff. The main risk-reduction measure is the development of GI as an integrated stormwater management system that requires cross-sector collaboration within municipalities.

Key words: cross-sectoral collaboration, green infrastructure (GI), integrated stormwater management, intensified renewal of combined sewer systems, low impact development (LID), no-dig

HIGHLIGHTS

- Trenchless rehabilitation of combined sewer systems (CS) in combination with low impact development (LID) can give a 60–90% cost reduction per meter compared to open-cut methods.
- An integrated stormwater management system (ISMS), including green infrastructure, should be implemented to avoid damage from uncontrolled stormwater runoff from LID.
- Cross-sector collaboration can contribute to intensifying rehabilitation of CS.

INTRODUCTION

An increasing need for investments in sewer network renewal

Water and wastewater services are vital functions in a society. To ensure that the sector provides good-quality services, the water and wastewater networks must be continuously rehabilitated and upgraded.

The EU countries spend an average of EUR 100 billion per year on water supply and sanitation (OECD 2020). Benchmarking of asset replacement and renovation investments per property for European cities selection showed considerable variations. In the analysis, the Norwegian capital Oslo reported the highest investment costs per household, at EUR 201 in 2019. This cost was more than twice as high as for second-ranked Hamburg in Germany (EBC 2019). The total annual cost of sewer network renewal in Norway averages EUR 250 million. Studies show that Oslo is among the municipalities in Norway with the lowest investment costs per household (The Norwegian Water Association 2019).

Despite sizeable annual investments, there is still a considerable sewer rehabilitation backlog due to ageing infrastructure. Investments in the EU are expected to increase to EUR 289 billion (OECD 2020) by 2030. In Sweden, calculations show that investments of EUR 46 billion are needed until 2040 to maintain the functionality

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of the infrastructure, further develop water and wastewater services and meet future demands (The Swedish Water Association 2020). This is an increase of 40% from today's investment level and amounts to about EUR 490 per household per year. In 2017, the need for investments in water infrastructure in Norway was estimated at EUR 28 billion by 2040 (Rostad 2017). In 2020, the Norwegian estimate was raised to EUR 32 billion (Breen 2020). This amounts to an annual cost per household of EUR 650. The estimated future investment needs for Norway's sewer network are based on the current unit costs and a rehabilitation rate of 0.9% (The Norwegian Water Association 2019). However, several municipalities have also made their own calculations of the necessary rehabilitation rate; for example, Oslo, where the rehabilitation rate is estimated to be 1.6%.

Pipeline renewal vs. replacement

The water sector in Norway can increase its efficiency and save considerable amounts on renewing the pipeline system by using trenchless technologies. For Norway, a 25% reduction in costs per meter pipeline renewed would result in an annual efficiency gain of EUR 175 million. In addition to reducing the direct costs, this is also an essential way to reduce the climate footprint of the sector. (The Norwegian Water Association 2019).

Municipalities can save considerable amounts when renewing underground utility systems by using a trenchless cured-in-place pipe renewal method (CIPP) (Kaushal *et al.* 2020). When planning the rehabilitation of pipelines, it is important to consider environmental impacts. A study for small diameter sanitary sewers in the City of Pasadena, California, USA, concluded that on average, CIPP renewal contributed 68% less environmental impact, 75% less impact on human health and 62% less resource depletion than the open-cut (OC) replacement (Kaushal & Najafi 2020). Although the expected lifetime for no-dig is shorter than for OC, trenchless methods performed well compared to OC due to the high sustainability factor (Bruaset Rygg & Sægrov 2018).

In 2019, the Agency for Water and Wastewater Services (AWW) in the City of Oslo invested EUR 76.8 million in pipeline renewal. Sewer system rehabilitation accounts for approximately 45% of total investments in Oslo. 29% of the rehabilitation cost are allocated to no-dig methods. In 2019, 2.1% of Oslo's sewer pipelines were rehabilitated. The high rehabilitation rate can be directly linked to the use of no-dig methods (City of Oslo 2019). No-dig account for only 29% of the costs but represents 73.8% of the pipeline rehabilitated.

Changing conditions due to climate change and urbanisation

In addition to reduced functionality due to aging, the wastewater networks are under further stress from rapid urban development and increasing rainfall due to climate change.

Climate change poses a challenge to planning and maintenance as the dimensioning for future needs becomes increasingly uncertain. For example, a rainfall event with a 20-year return period in Norway is expected to increase by 27–46% by 2100, depending on rainfall duration (Dyrrdal & Førland 2019). Climate change projections call for more frequent and more intense rainfall events, more frequent freeze-thaw cycles and a larger share of winter precipitation falling as rain. Summers will see increasing numbers of droughts (Hanssen-Bauer *et al.* 2017).

In 2018, 55% of the world's population were living in urban areas. This share is expected to grow to 68% by 2050 (United Nations 2019). In Europe, the level of urbanisation was already 74% in 2018 but is expected to continue to grow in the coming years (Margaras 2019; United Nations 2019). According to projections, the population of the Norwegian capital will increase to about 850,000 in 2040, which is 25% more than in 2019 (City of Oslo 2020). Urbanisation causes an increase in impervious surfaces, which leads to both more stormwater runoff and faster response, resulting in increased risk of sewer network overload.

In recent years, a large number of different types of precipitation-related damage have been registered in Norway. According to Finance Norway's database, total insurance payments for precipitation-related damages amounted to EUR 700 million between 2008 and 2020 (Finance Norway 2020). Thirty per cent of these damages are directly linked to the wastewater network. Like many other European cities, large sections of Oslo's wastewater network are a combined sewer system (CS), collecting domestic sewage and stormwater runoff in the same pipe. These systems are not designed to cope with increasing amounts of stormwater, thus contributing to increased sewage overflow and more extensive and frequent infrastructure damage. Uncontrolled sewage discharge can increase risks to human health and the environment.

After rehabilitating pipelines that still have sufficient capacity, the challenge will be to identify pipeline segments suitable for no-dig solutions. However, continuing to use traditional OC as the only method for capacity improvement will increase rehabilitation costs and create a faster reduction in functionality of the wastewater infrastructure if the budgets are not increased.

LID reduces damages caused by the sewer system

Many municipalities experience a frequent overload of their sewer systems, resulting in floods and the discharge of untreated sewage. By disconnecting some areas from the system, one can reduce the load from stormwater and thereby reduced the need for replacement of the pipes. To reduce leakage and infiltration the pipes can be rehabilitated with no-dig methods, such as pipelining (Sörensen 2018). Stormwater disconnection can be managed by low impact development (LID) as an alternative land development approach for stormwater management close to the source. LID reduce the impact of development on the local hydrological conditions through the use of bioretention, green roofs, grass swales, and permeable pavements that infiltrate, evaporate, or harvest and use stormwater on the site where it falls (Shafique & Kim 2017). Reducing surface runoff by increasing infiltration was tested in Oklahoma, USA, using various surface-based stormwater solutions. Disconnection of stormwater from impermeable surfaces such as roads, parking lots, sidewalks and buildings led to a reduction in peak load on the sewer network during precipitation and improved water quality in watercourses due to a reduction in overflow discharges (Ruiz Vogel & Taghvaeian 2017). Silva & Silva (2020) point out that there are several uncertainties associated with disconnecting impermeable surfaces. LID is more effective for reducing stormwater runoff with shorter rain duration and smaller rainfall events. Disconnection of impermeable areas on a large scale can change runoff patterns and increase surface runoff. The risk increases at a high decoupling rate combined with low infiltration (Silva & Silva 2020).

GI copes with uncontrolled stormwater

‘Green Infrastructure can be broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings’ (European Commission 2013). Key findings from an Australian study on stormwater management using imitation of natural hydrological processes indicate that GI’s intensive application can significantly reduce flood depth and drainage velocity. However, residual risk remains, especially during extreme flood events (Webber *et al.* 2019). A recent study from China concludes that GI helps reduce the increased stormwater runoff and flood risk in urban areas by providing regulation functions (Li *et al.* 2021).

Objectives

As described above, the benefits of using no-dig for the rehabilitation of sewer networks are documented (Kaushal & Najafi 2020; Kaushal *et al.* 2020). There are also good examples of using LID to reduce peak loads to the wastewater system (Ruiz Vogel & Taghvaeian 2017; Silva & Silva 2020). Green infrastructure can be applied to minimise damages caused by uncontrolled surface runoff (Webber *et al.* 2019; Li *et al.* 2021). However, we have not identified practical examples of combining these management approaches for CS renewal and CS capacity improvement. It is also uncertain if water and wastewater network (WWN) owners can accept the risk of potentially increasing uncontrolled surface runoff by implementing LID by themselves for improving the sewer network’s capacity in existing developed areas or if it is necessary to combine LID with GI.

This study aims to develop a method for evaluating no-dig, LID and GI as an alternative for improving the quality and capacity of the CS. The methodology is tested in a case area in Oslo.

METHODS

Calculations of cost savings from increased use of no-dig

As motivation and pre-analysis for the main study, we investigated how the choice of rehabilitation methods affects the rehabilitation rate of the wastewater network of Oslo.

The calculations were based on the AWW’s wastewater rehabilitation budget for 2019 (B), unit costs for no-dig (N) and open-cut methods (OC), a rehabilitation target rate of 1.6% (G) and the total length of Oslo’s sewer network (L). The values for input parameters and equations for output at the variable share of no-dig (S) are shown in Table 1.

Table 1 | The values for input parameters and equations for calculation of cost savings from increased use of no-dig

Parameter	Abbreviation	Value/formula
INPUT		
Budget, EUR/year	B	34,500,000
Unit cost for no-dig, EUR/m	N	408
Unit cost for open-cut, EUR/m	OC	3,608
Rehabilitation target rate, %	G	23,840 (1,6%)
Total length of sewer network, m	L	1,490,000
Share no-dig, %	S	From 0% to 100% with variation $s + 1 = 10\%$
OUTPUT		
Cost no-dig, EUR	CN	$G \times S \times N$
Cost open-cut, EUR	COC	$G \times (100\% - S) \times OC$
Total rehabilitation cost, EUR	T	$CN + COC$
Reduction in unit costs, %		$100\% - (100\%/AC_s \times AC_{s+1})$
Average cost per meter, EUR/m	AC	T/L
Goal achievement, EUR		B/T

Concept assessment methodology

The study was carried out according to the framework of the Norwegian quality assurance scheme (QA scheme) for major public investment projects in the City of Oslo (City of Oslo 2011). An essential principle of this framework is to perform a thorough analysis of needs, goals and requirements in the project area before considering various options for problem solving (Figure 1). The methodology enables an unbiased analysis of alternative measures to identify a specific project's most suitable concept.

The overall need for all infrastructure in the trench is important for prioritising projects and selecting technical solutions. As water and sewer pipelines in Norway often run in the same trench, the water supply system is also assessed in projects initially initiated by the need for upgrades of the sewer network and vice versa. On the other hand, QA scheme has never been used in Oslo to assess LID and GI to solve CS capacity problems.

In traditional wastewater system assessments, the emphasis is on hydraulic analysis, although hydrological processes are also used for pipeline design. In evaluations of stormwater runoff, hydrological analysis is predominant. Thus, two disciplines must be equally considered when including assessments of LID and GI in a wastewater rehabilitation project: hydraulics and hydrology. A complicating factor in such a process is the division of sector responsibilities between the various departments in a municipality. Whereas WWN owners, for example in Norway, are focussed on reducing basement flooding and combined sewer overflows (CSO), the responsibility for property damages from uncontrolled stormwater runoff lies with private and public property owners. It is challenging to coordinate such diverging interests without a well-established collaboration between the various stakeholders (see column C in Figure 2).

This study is based on the current model of how responsibilities are divided; that is, without clearly defined interdisciplinary collaboration. Methodologically, it involves a combined study of hydraulic drainage area and hydrological catchments, with the subsequent assessment of both piped- and surface based- capacity-enhancing

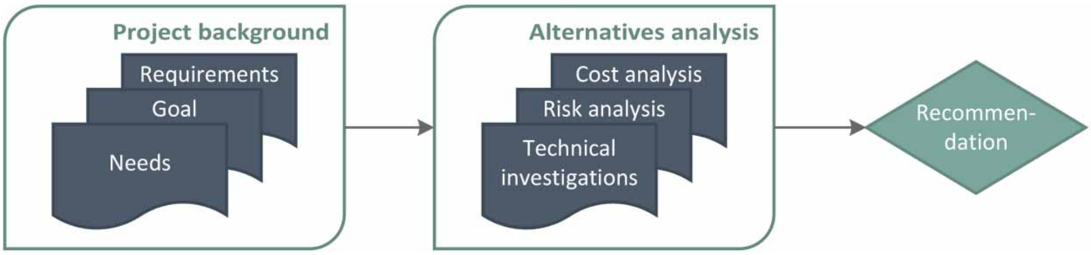

Figure 1 | Basic principles of the concept selection study.

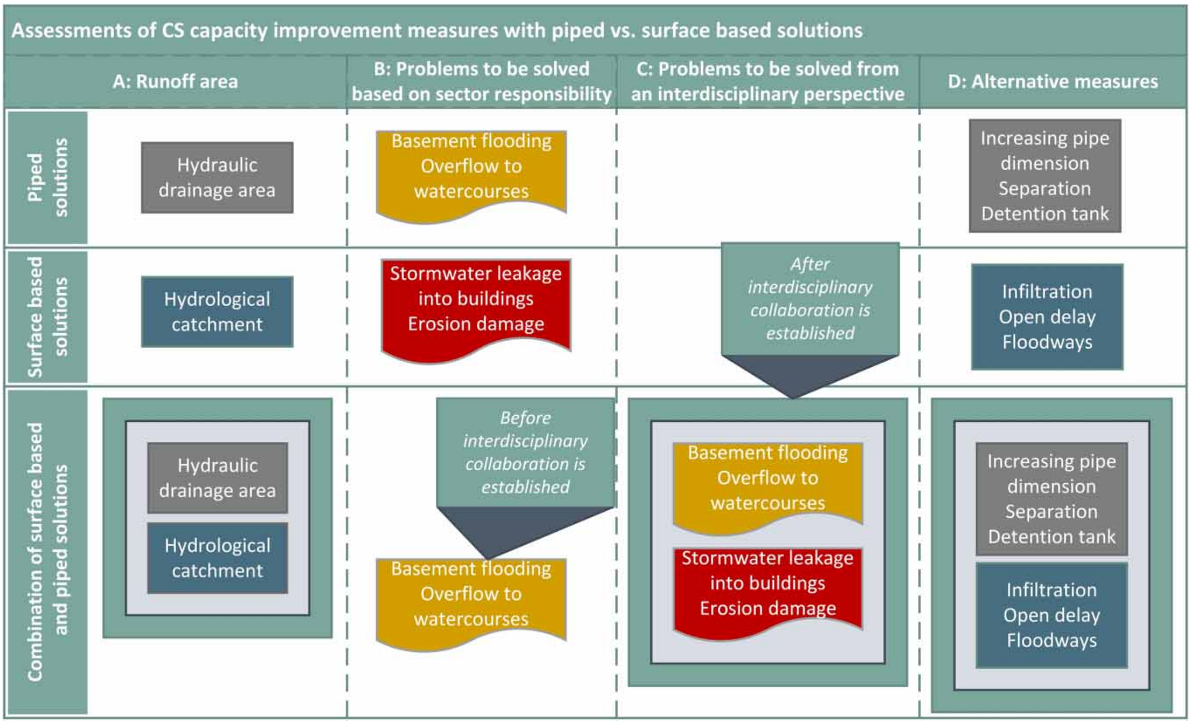

Figure 2 | Assessments of CS capacity improvement measures with piped vs. surface-based solutions for surface runoff.

measures. Meeting the needs of WWN owners; that is, reducing basement flooding and CSO, is defined in this study as an absolute requirement. The potentially reduced risk of stormwater damage is seen as a positive side effect (Figure 2).

Case area

The wastewater network in Oslo has a total length of 2,250 km (City of Oslo 2020), with an average age of 47 years. The oldest pipelines are more than 100 years old. Approximately 55% of the wastewater network in Oslo is CS. The network includes 218 CSO that discharge into the city's watercourses and the Oslo Fjord.

The case area is located in the Gaustadbekken catchment in the northern part of Oslo (Figure 3). The total area of the catchment is 3.5 km^2, of which 84% is urban area. Numerous smaller streams drain into the Gaustadbekken stream, several of which have been piped in the past due to urban development. The upper part of the catchment is located at about 200 meters a.s.l. The Gaustadbekken stream drains in to the river Frognerelva at about 64 meters a.s.l., giving an average slope of 8%. In the upper part of the catchment, the case area consists of single-family homes and large private gardens. Most of the roads are distribution streets throughout the residential area. The wastewater network consists mainly of CS.

Prerequisites to study

Within the catchment area, numerous sewage and stormwater-related incidents have been recorded through the years: basement floodings, CSO discharges into watercourses and flooding of buildings and land from uncontrolled surface runoff of stormwater. In 2016, a concept study was performed to avoid the recurring basement flooding from the CS in five houses (City of Oslo 2016). Three types of measures were considered to solve CS capacity: separating sewer and stormwater flows, increasing pipe dimension and installing a detention tank. Although the city of Oslo approved a stormwater strategy that promotes surface-based and local stormwater management (City of Oslo 2013b), the WWN owner could not consider the application of GI. This was due to the stringent full cost recovery regime, which stated that the water and wastewater fees should only finance pipeline projects (The Norwegian Ministry of Local Government and Modernisation 2014). The feasibility study recommended an increased capacity of CS at the cost of approximately EUR 4.4 million.

Before the final approval of the initial separation project, the possibility arose to use water and wastewater fees for LID and GI that relieve the strain on existing municipal sewer networks and treatment plants (The Norwegian

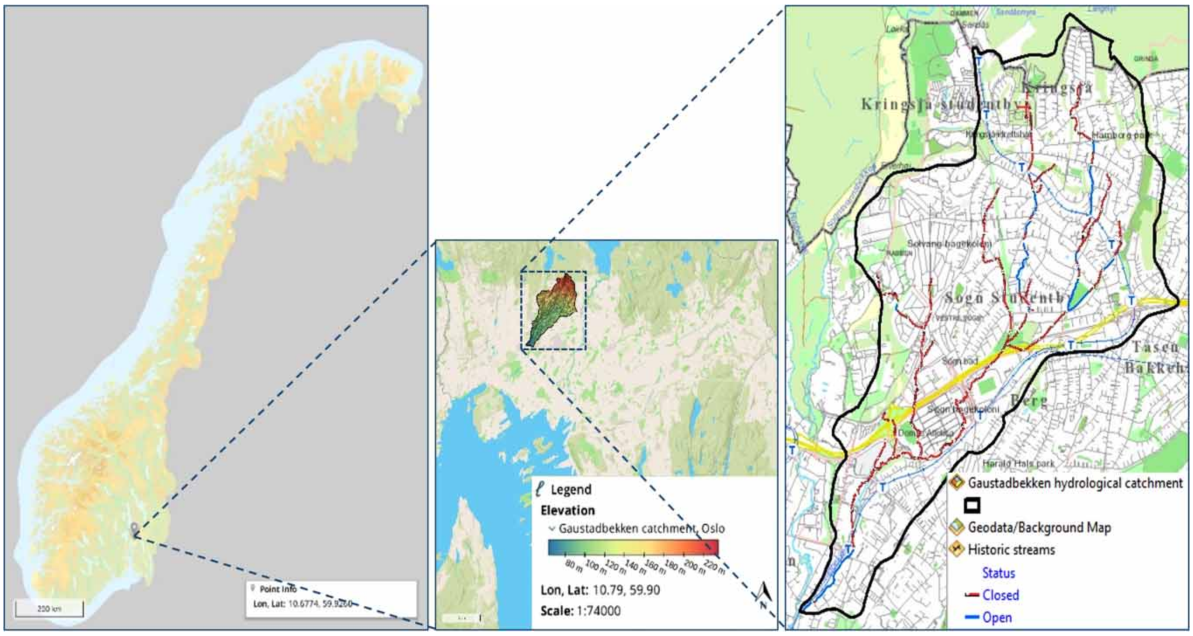

Figure 3 | Case area localisation.

Environment Agency 2019). This change provided the opportunity to consider using LID and GI as an alternative to increasing the combined sewer network capacity and solve the basement flooding problems. Municipal service providers in Norway are authorised to order the disconnection of stormwater runoff from impervious surfaces by the Pollution Control Act section 22 (The Norwegian Ministry of Climate and Environment 1983). Thus, a new study was commissioned, which specifically required an assessment of downspout disconnection as an alternative measure to resolve the sewage network's insufficient capacity.

A review of registered damages in the case area showed that new incidents had occurred since the previous study: basement flooding, frequent sewer overflow to the Gaustadbekken and stormwater damage to houses. All of these cases were related to heavy rainfall events and peak discharge to the CS.

Stormwater runoff in the entire catchment area

To get an overview of the hydrological runoff pattern in the catchment and get an idea of the potential risk of uncontrolled surface runoff, an extreme precipitation event was modelled in a non-calibrated Stormwater runoff model, MIKE21 (MIKE21 2019), with a grid size of 4×4 meters for the Gaustadbekken hydrological catchment. The simulations were carried out with an actual rainfall event of 155 mm in 135 minutes, which hit Copenhagen on 2 July 2011 (Lindholm Buhler & Bjerkholt 2013).

The CSO effect on the water quality of the recipient was assessed from routine water quality measurements in the watercourses and analysed against data on overflow events. Data on basement flooding damages from backlash, stormwater-related complaints and CSO events were retrieved from the AWW database (Figure 3). Registered stormwater damages were compared with the results from the MIKE21 calculations. Mapping the status of drainage pathways and existing depressions and assessing LID and GI possibilities were performed during site inspections.

Identifying sources of I/I-water

'Infiltration and inflow water (I/I-water) include rainfall, groundwater, and leakages from the water supply system. I/I-water finds its way into the wastewater network through damaged pipes, damaged manholes and faulty connections, but can also enter the network intentionally, which is the case for rainwater in a combined sewer system' (Sola *et al.* 2018). In AWW's master plan, I/I-water in the case area was calculated to be 64–72% (City of Oslo 2013a). I/I water influx into the wastewater system can be divided into diffuse infiltration via water supply leakage and direct inflow. Diffuse infiltration was examined by detecting infiltration in manholes during the dry-weather site inspection, CCTV (closed circuit television) of all sewer pipelines and acoustic leak detection. These inspections were performed to provide the necessary data for assessing the condition of manholes and pipelines to choose the appropriate rehabilitation measures. A general reduction of I/I water was not defined as a requirement by AWW. Thus, no further investigations of I/I water sources were made, such as measuring the groundwater level and measuring pipeline temperature. Since all recorded damages in the case area occur during heavy rainfall events, priority is given to investigating the sources for a direct inflow of I/I water that result in peak discharge to the CS.

An information letter was sent to all inhabitants within the hydraulic drainage area to notify them of upcoming site inspections. For each building, the number of downspouts that could be connected to the CS was recorded during an inspection. Disconnected downspouts that drained onto impervious surfaces were also recorded.

There are no maps for road drainage pipes in Oslo. To identify recipients of road drainage pipes, a terrain analysis was performed in ArcGIS to assess road slope towards watercourses and existing stormwater drainage pipes. The tested hypothesis was that road drainage often follows the road's slope. The digital terrain analysis was verified by tracing road water on one road in the area by adding the tracer dye Uranine in gullies and then looking for discolouring in nearby aqueous recipients and CS manholes. The assessment of the need for treating road runoff was based on an analysis of the area's traffic load (annual average daily traffic) (The Norwegian Public Roads Administration 2008).

Alternatives analysis

The selection of alternative concepts was based on the premise that pipeline capacity can be increased either by reducing the influx of I/I water or by up-sizing the pipe. In addition to upgrading existing conditions, two basically different solutions were identified:

- Alternative 0 (A0) – Upgrade of status quo with no-dig and LID.
- Alternative 1 (A1) – Rehabilitating pipe using no-dig, LID and GI.
- Alternative 2 (A2) – Removing bottleneck.

In literature, many terminologies for different surface-based solutions are used interchangeably (Fletcher *et al.* 2014). In this study, terms for LID and GI are linked to three steps in stormwater strategy in Oslo (City of Oslo 2013b). LID means step 1 for handling smaller amounts of precipitation locally, while GI covers steps 2 and 3 with stormwater diversion and safe surface transportation.

Alternative solutions were assessed in terms of meeting the 'must' and 'should' requirements, as defined by the study, based on hydraulic modelling results. A qualitative risk analysis of all three alternatives concludes with a recommendation of the alternative solution that best meets all requirements. A simple cost analysis of investment costs was performed for the recommended alternative, based on AWW unit prices.

Hydraulic modelling

Modelling of the existing conditions and the effect of alternative solutions was performed with a hydraulic model for wastewater systems, using the MIKE URBAN Collection System (MUCS) (MIKE URBAN 2019). Runoff from rainfall depends primarily on the size of the catchment, land use and land cover. To describe changes in rainfall runoff over time, the Rainfall-runoff module in MUCS was used. Essential parameters are catchment size, initial loss, hydrological reduction factor and concentration time. Using these inputs, rainfall-runoff is calculated according to the time-area method. Based on the collection of field data, all catchments were updated concerning the permeable surface ratio. The predicted runoff was then linked to the hydraulic module in MUCS to calculate the temporal variation of water flow and water level in the wastewater network. The model was calibrated to an actual runoff in 2015. A re-calibration was considered unnecessary since the simulation of specific rainfall events in 2019 showed that the model results agreed well with the damages reported for these events.

Three precipitation scenarios were run for all three alternative concepts. Overflow discharge in the case area should not occur more than once every two years, and there should be no repeated basement flooding from sewer backups during 30-year rainfall events in the future Oslo applies a climate factor (CF) of 1.5 for future precipitation (City of Oslo 2014). To evaluate the effect of the measures on overflow discharge for future rainfall as well, simulations were run for 2-year rainfall events, including CF. Intensity-duration-frequency curves (IDF) are developed based on statistical precipitation data from the weather station at Blindern, Oslo (1967-2019) (The Norwegian Meteorological Institute 2019).

RESULTS AND DISCUSSION

Potential cost savings from increased use of no-dig in Oslo

The importance of using no-dig technology for the achievement of a 1.6% rehabilitation rate in Oslo was analysed based on the equations in Table 1. This showed that at the current level of investments by AWW, one would have to rehabilitate more than 60% of the pipelines using no-dig technologies to meet the target (Figure 4). At a no-dig share above 70%, it is possible to rehabilitate more than 1.6% or spend less than budget. Variation in cost for no-dig, OC and goal achievement follows the left y-axis. The average cost of a rehabilitated meter of pipe is reduced by increased use of no-dig (x-axis) and follows the right y-axis.

The calculations show that unit cost reductions increase with an increasing share of no-dig. The cost of OC projects varies between EUR 1,000 and EUR 4,000 per meter, depending on local conditions. There is much less variation in unit costs for no-dig. The cost reduction per rehabilitated meter of pipe using no-dig instead of OC thus amounts to between 60 and 90%. A sustainability factor should be included when assessing the most suitable rehabilitation methods at different locations to consider the expected shorter service life for no-dig (Bruaset Rygg & Sægrov 2018). By including in the calculation side effects of no-dig such as less environmental impact, less impact on human health, and less resource depletion (Kaushal & Najafi 2020), an even higher sustainability factor will be achieved than just by assessing investment costs.

Practically, however, achieving a large share of no-dig would be challenging due often to the low capacity of CS in Oslo. Therefore, different alternatives for solutions that can increase CS capacity must be evaluated.

Alternative solutions

A map of the evaluated solutions, including the solution proposed by the concept study from 2016, is shown in Figure 5. A0 corresponds to the existing situation, only a few upgrades are done to maintain the sewer network's current operations without extensive investments. These upgrades are a no-dig rehabilitation of 270 m of CS, mandatory downspout disconnect representing 6.5% of connected impervious surfaces or 33% of all impervious surfaces in the catchment in the wastewater catchment area, and infiltration of roof runoff on private property.

A1 consists of a no-dig rehabilitation (270 m), as for A0, and LID to deal with 1% of connected impervious surfaces in a small, closed sub-catchment that drains directly to the CS, and which contributes to overloads and overflows with about 50% of roof runoff and all road runoff. Disconnected roof runoff shall be infiltrated on private property and diverted away from paved driveways. Road runoff will be diverted, retained and infiltrated in an infiltration trench and bioretention cells on a street (GI). Due to the low annual average daily traffic, road runoff does not need treatment. The GI measures will reduce the road width. It is not possible to openly divert the water from the GI to a recipient without removing any buildings, and it is far from the

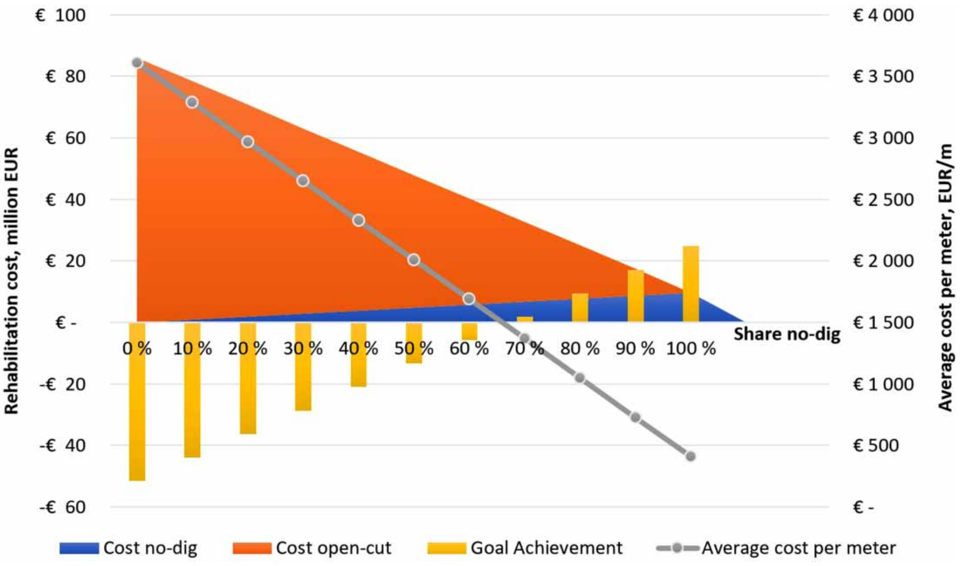

Figure 4 | Goal achievement for sewer network rehabilitation and savings, given a fixed annual budget of EUR 34.5 million and a varying share of no-dig. The calculations are based on the equations in Table 1.

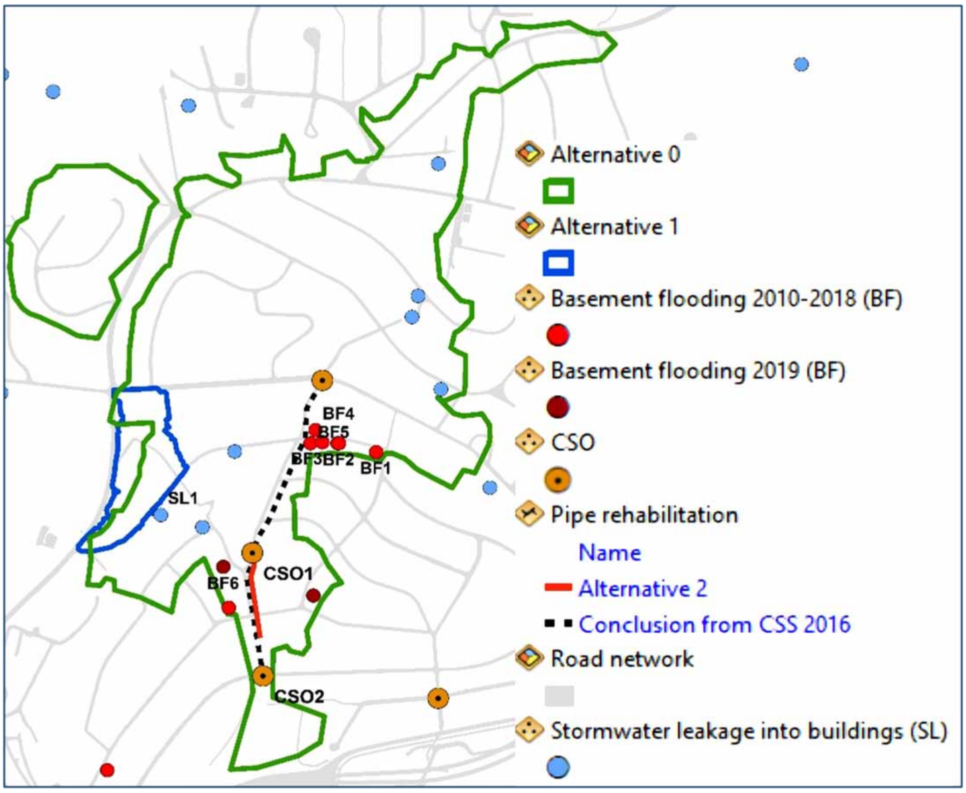

Figure 5 | Alternative solutions for rehabilitation.

downstream stormwater pipeline. A controlled overflow from the GI to the existing CS is thus needed to cope with rainfall events that exceed the system's capacity.

A2 involves an up-sizing of the CS pipe diameter downstream from the overflow CSO1 from Ø300 to Ø500. For this alternative, it is also necessary to replace the water supply pipe due to the small distance to the sewer pipe. Pipe cracking is not possible, which would be a more environmentally friendly alternative.

Effects of the alternatives

Results of the downspout disconnect in the drainage area in A0 show that by reducing runoff from impervious surfaces by 33%, which corresponds to 50% of the roof area in the drainage area, the discharge is significantly reduced from both CSOs (Table 2). Also, problems linked to basement flooding and CSO are solved for design rainfall events. The risk of stormwater damage at SL1 (Figure 5) is reduced but not altogether avoided. With this alternative, there will still be a lot of road runoff draining to the CS. Measures associated with A1 resolve the problems linked to stormwater damage SL1. The risk of CSO1 and CSO2 and local basement flooding is

Table 2 | Modelling of alternative scenarios and effects on CSO

	Model assumptions				**Model results**					
					Calculated discharge from CSO1 (m^3)			**Calculated discharge from CSO2 (m^3)**		
Total areal = 58.3 Ha roof 12.9% road 7.5%	**Share of total area connected to the CS**	**Share of roof area connected to the CS**	**Share of road area connected to the CS**	**CS dimension downstream from CSO1**	**2-year rain**		**30-year rain**	**2-year rain**		**30-year rain**
						+CF	**+CF**		**+CF**	**+CF**
Status	10.9%	6.5%	4.4%	Ø300	27.97	29.4	134.4	124.4	189.8	816.9
A0	4.4%	0	4.4%	Ø300	0	0	21.9	0	0	231.1
A1	9.9%	6%	3.9%	Ø300	0	9.76	51.7	3.2	137.23	737.4
A2	10.9%	6.5%	4.4%	Ø500	0	0	0	0	210.5	940.4

considerably reduced, and there is some reduction of the basement flooding risk on a nearby street due to reduced loads to the CS on an upstream road during rainfall events. There is also a generally positive effect from A0 and A1 on the CS downstream.

Up-sizing under A2 contributes to reducing the risk of basement flooding and CSO1. However, the loads are passed downstream more quickly and contribute to an increase in overflow discharge from CSO2. Alternative A2 also does not reduce the risk of stormwater damage SL1. The analysis of the model results for all alternatives shows that up-sizing has a positive local effect but does not help solve problems upstream while also creating new problems downstream. However, disconnection of impervious surfaces generally contributes positively to overcoming the challenges in the case area, including improved water quality in the river Frognerelva.

The effect of all alternatives on CSO was assessed by studying the model results for CSO discharge for different rainfall scenarios. An example for future 30-year rainfall events is shown in Figure 6.

A rough classification of the alternatives, according to the must-requirements, is summarised in Table 3. Even though A2 is feasible for the WWN owner, it does not provide the desired effect. The cost-effectiveness of the investment is low, as up-sizing leaves network capacity underutilised for most of its lifetime. The alternative is rejected after this rough classification. An assessment of the remaining alternatives, A0 and A1, according to the should-requirements (Table 3) concludes that both could be recommended as practical solutions. However, A1 provides more added value to the project in the short term.

Both A0 and A1 have positive effects on environment and climate: less runoff is transported out of the watershed by pipe and compared to OC projects, the economic cost for implementation of the measures is less. Both alternatives reduce peak loads in the CS downstream the case area, which reduces energy consumption for wastewater pumping and treatment. A1 also provides added value in increased urban green space and reduced traffic in the residential area. The measured effect in the study agrees well with results from a study of CSO control with

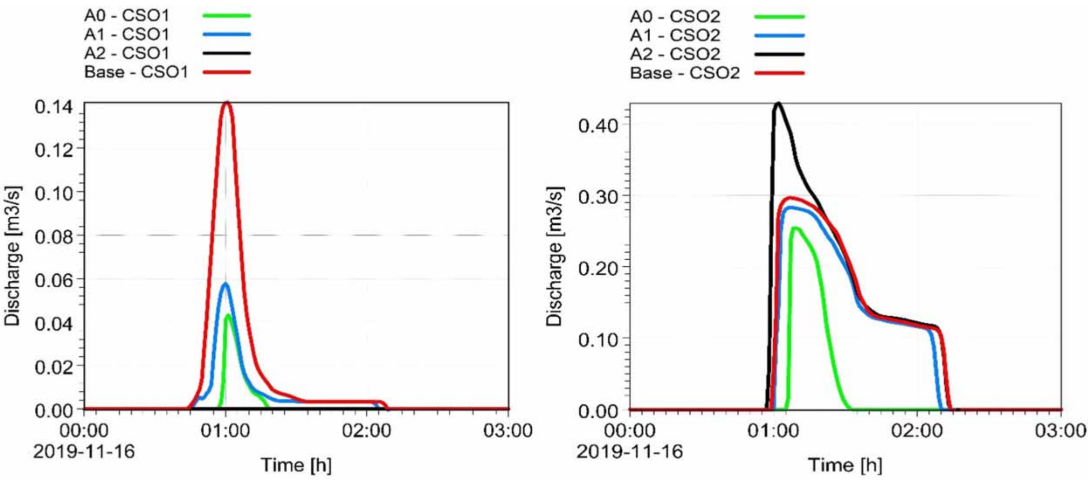

Figure 6 | Effect of future 30-year rainfall events on discharge from CSO1 and CSO2.

Table 3 | Classification of alternatives (A0, A1, A2) after requirements to the study (0 does not meet requirement, + meets requirement partially/uncertainly, ++ meets requirement completely)

Requirements		**A0**	**A1**	**A2**
MUST	Avoid basement flooding BF1-6, future 30-year rainfall	++	++	++
	CSO1 discharge must not occur at <2-year rainfall	++	++	++
	CSO2 discharge must not occur at <2-year rainfall	++	++	0
SHOULD	Stormwater leakage to building SL1 should be avoided	+	++	
	Establish cross-sectoral pilot project for LID and GI development	0	+	
	Establish LID/ GI if such measures take pressure off CS	+	++	
	Priority given to solutions that result in zero or least greenhouse gas emissions	++	+	

LID in Shanghai, China (Liao *et al.* 2015). LID alone cannot solve problems on the CS. However, combining these either with piped solutions or with GI can give the desired effect. Besides, the choice of type GI may affect the runoff after the implementation of measurements. A study from Canada documents that GI solutions such as infiltration trenches and bioretention cells stand out positively from other surface-based solutions with a particularly good effect on reducing surface runoff (Joksimovic & Alam 2014).

Risk analysis and recommendation

An expected positive effect on CS capacity was shown for A0 and A1. However, there are some uncertainties due to little experience with LID and GI projects in Oslo. Specifically, large uncertainties are associated with challenges during construction etc. Maintenance is essential to ensure the long-term functionality of surface based stormwater solutions. It is thus necessary to establish maintenance routines and secure sufficient funding.

To achieve the desired effect of disconnecting downspouts in A0 and A1, it is crucial that roof runoff is retained and infiltrated on private property. Including LID on private property as part of a municipality's wastewater management may involve a risk due to uncontrolled runoff. The degree of the project's success depends on human factors such as skill, determination and know-how. Education of the community in the area on why these measures are needed and how they should be implemented will increase the likelihood of success. The development of a municipal programme providing financial support for establishing LID on private property would presumably contribute to achieving the desired results (Barclay 2016). This would require the municipality to be well organised and have sufficient staff resources with the necessary know-how about sustainable drainage systems and public outreach skills. When disconnecting downspouts, the potential risks of improper execution must be considered:

- The runoff could enter the drainage system, adjacent properties or public roads.
- If roof runoff entered the building's drainage system too quickly, the desired reduction of load of CS would not be achieved.
- Runoff entering neighbouring properties could lead to stormwater damage on those properties.

The case area has considerable terrain variations, resulting in high stormwater velocities, thus, a high risk of damages during heavy rainfall events (Figure 7).

A combination of parameters water velocity and water depth can lead to injuries (Martínez-Gomariz *et al.* 2016). Vehicles can move in the water flow at speeds from over 0.48 m/s at varying water depths, depending on the type of vehicle (Bocanegra Vallés-Morán & Francés 2020). With rapid surface runoff, stormwater will

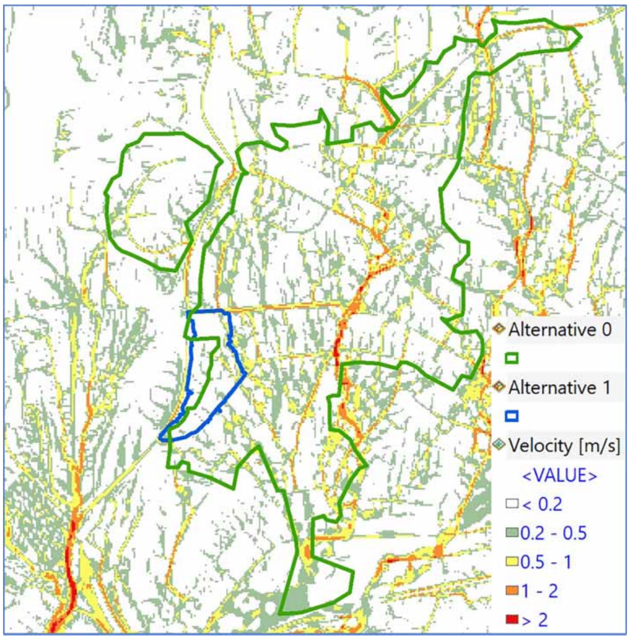

Figure 7 | Velocity in the case area. MIKE21 model results.

not be able to infiltrate. Disconnected roof runoff could flow quickly to the public road network. This could increase negative adverse effects from heavy rainfall, such as damage to other properties, road erosion, sewer system overload, and water bodies pollution. This assessment is consistent with the conclusion of Silva & Silva (2020). A summary of incidents and the consequence that the analysis is based on are presented in Table 4.

Presenting the results in a risk matrix (Figure 8) clearly shows that A2 involves the lowest risk for most of the identified risk incidents. The main problem with A2 is that the alternative does not reduce the loads on CS downstream. The A0 is associated with high risk. The WWN owner should not uncritically disconnect impervious surfaces for CS capacity increase even though that would relieve the pressure on the CS. It would be necessary to carry out risk-reducing measures before including this alternative in the project portfolio. The risk level of A1 lies between the risks associated with A0 and A2. This alternative cannot solve all challenges linked to network capacity in the drainage area, but it can reduce the risk of CS damage from heavy rainfall events.

To reduce the risk of uncontrolled stormwater runoff, it is recommended to divide the disconnection of impervious surfaces into several phases, beginning with A1. AWW can mainly carry out the disconnection of impervious surfaces and GI implementation inside an A1 area. The maintenance of the installations must be clarified with the road owner, the Urban Environment Agency in Oslo. The disconnection of downspouts in other parts of the drainage area in A0 should be gradually introduced since the municipality's strategy is to establish controlled stormwater runoff in the area. Planning and implementing the integrated stormwater management system (ISMS) is an interdisciplinary challenge involving numerous stakeholders. Such a task requires the cooperation of the involved sectors within the project organisation and additional, more detailed interdisciplinary studies of the stormwater system. The municipality must ensure the safe diversion of stormwater that is not dealt with on private property.

Table 4 | Summary of risk incident and consequence

Risk	Risk incident	Consequence
R1	Residents not able and willing to implement LID correctly.	High I/I flows to the CS and additional stormwater damage.
R2	Insufficient capacity for local infiltration of roof runoff.	High I/I flows to the CS and stormwater damage.
R3	Disconnected roof runoff discharged too quickly to public road network.	Stormwater damage.
R4	High road runoff velocity from steep road segments.	Erosion damage on roads.
R5	Local recipients unable to cope with increased quick surface runoff.	Damages to properties along open streams.
R6	Effect of downspout disconnect on reduction of peak loads to the CS overestimated by model calculations.	Basement flooding and sewer overflows not solved.
R7	Difficulties in organising cross-sector collaboration.	Continued stormwater damage. Municipality's reputation declines.
R8	GI in public spaces does not have desired effect because of insufficient maintenance.	Flooding, overflow discharge and basement flooding continues.
R9	Strain on the CS downstream from project area not reduced.	Potential increase of damages downstream.

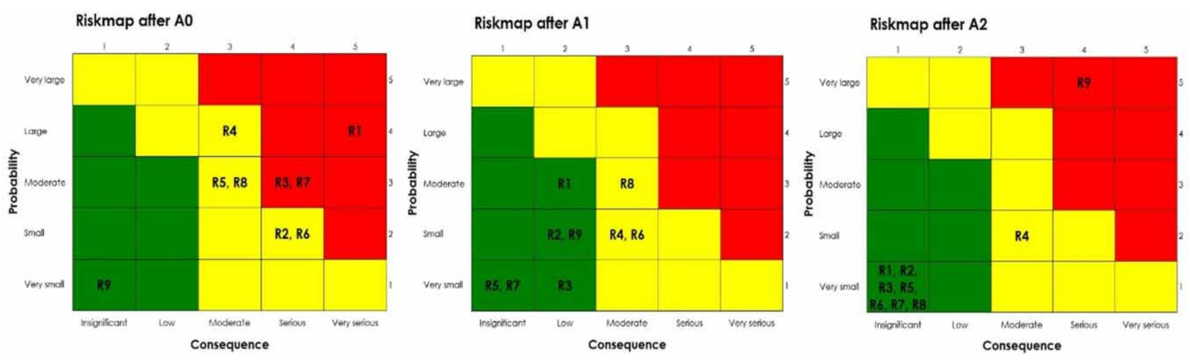

Figure 8 | Risk matrix after having completed measures in A0, A1 and A2.

Cost analysis

Downspout disconnect in A0 and A1 would not require investments by the WWN owner, although the measure entails administrational costs for the exercise of authority. Implementing A1 would be most beneficial with respect to the lowest risk. The calculation of investment costs for A1 is based on AWW unit costs (Table 5). When calculating total project costs, AWW add 15% for contingencies and 30% for administrational overhead (project management, project planning and design, construction description). Operational costs are not assessed as part of concept selection studies at AWW since the existing operating budget will cover these.

This study recommends measures requiring an investment of slightly more than EUR 200,000. This is more than 95% below the original estimate of EUR 4.4 million from 2016. The considerable reduction is the result of having chosen a completely different approach to solve the problem. An analysis of life-cycle cost has not been performed in the study. However, although no-dig, LID and GI service life is shorter than for OC rehabilitation, these alternatives will have a high sustainability factor and high cost-efficiency in terms of unit costs of removal of a single m³ of runoff due to low investment costs and several positive side effects of these measures (Joksimovic & Alam 2014; Bruaset Rygg & Sægrov 2018).

Reliability

The assessment of different solutions to the problem provided sufficient information to recommend the disconnection of impervious surfaces as an alternative to increase CS capacity. However, there are some uncertainties (Table 6). The two factors of the most significant importance for the reliability of the results are downspout registration and the lack of an coupled hydraulic model for stormwater runoff and CS. There is also some uncertainty regarding the reliability of data from CSO registrations and hydraulic drainage modelling. Eliminating the uncertainties of investigated factors increases the reliability of the study's results.

When visually inspecting downspouts, it cannot be seen if all downspouts that lead into the ground are connected to the CS or if roof runoff infiltrates in other structures, such as a stone reservoir. On the other hand, not all disconnected downspouts are «off the hook»: there is still a risk that roof runoff infiltrates the house's

Table 5 | Cost estimate for the recommended alternative A1. cost, including contingencies costs and overhead (rounded to the nearest thousand)

Measure	Unit price	Total unit price, including contingencies costs and overhead	Cost A1
No-dig (240 m), EUR/m	270	400	72,000
Bioretention cell (40 m^2), EUR/m^2	670	1,000	40,000
Infiltration trench (170 m^2), EUR/m^2	400	600	100,000
Total, EUR			**212,000**

Table 6 | Reliability of pre-project inspection data

	Data reliability		
Factors	High	Medium	Low
Basement flooding	x		
Building damage from stormwater runoff	x		
CSO registrations		x	
Acoustic leak detection	x		
Registration of downspouts			x
Tracing of road runoff	x		
Mapping of drainage pathways and depressions	x		
Hydraulic modelling of drainage system		x	
Hydraulic modelling of stormwater runoff			x

own underground drainage or runs off on the surface. To reduce this uncertainty, technical documentation for all downspouts should be provided by all homeowners.

Even though the calculations were performed with a calibrated hydraulic runoff model, there is always a risk that main results deviate from reality. The model is calibrated for regular rainfall events, but dynamics can change when using design rainfall corresponding to a future 30-year rainfall event. The results can be too optimistic and not give the expected reduction in peak loads to the CS. As a consequence, the risk of basement flooding and watercourse pollution will remain. The need to increase CS capacity either by up-sizing or separation can thus not be written off before the downspout disconnect has been implemented and evaluated. In this context, it is necessary to carry out a 6-month measurement campaign of water flow in CS in the summer after having disconnected runoff from impervious surfaces and implemented GI before a final decision is taken about whether to rehabilitate the pipeline segment with insufficient capacity with no-dig or with OC. Implementing a module for calculating the pollution load from the CSO to the recipient will also help provide a better decision-making basis. The installation of measuring instruments that enable the determination of pollutant concentrations at the CSO would contribute to this parameter's calibration.

Modelling stormwater runoff with a rough, non-calibrated model provides sufficient stormwater runoff information for overall risk analysis in this study. For planning stormwater measures in an urban environment, there is a need to develop a more detailed integrated hydraulic model that describes runoff interaction on the surface and in the pipes.

CONCLUSIONS

There is a potential for considerable cost savings by increased use of no-dig methods when rehabilitating old CS. Based on the rehabilitation objectives for the city of Oslo and unit prices, calculations conclude that potential savings can be 60-90% per meter pipe when using no-dig instead of open-cut methods.

In this study, three alternatives with two different approaches to increasing CS capacity/reducing load were examined to evaluate the possibility of using no-dig for CS with insufficient capacity. The two approaches are a reduction of I/I-water from rainfall and the up-sizing of the CS. Alternative A3, with an up-sizing of the CS, was rejected as it did not meet all requirements. A reduction of peak loads to the CS using LID, as assessed in A0 and A1, allows a more extensive application of no-dig methods when rehabilitating old CS. Even if the measures in A0 should reduce investment costs for CS rehabilitation, a WWN owner should not disconnect impervious surfaces without conducting a risk analysis. Uncontrolled runoff after disconnecting impervious surfaces can lead to increased damages. Thus, it is necessary to establish an integrated, mainly surface-based (GI) stormwater management system (ISMS) before or concurrently with the WWN owner demand to disconnect impervious surface runoff. Such ISMS for all catchments would form a factual basis for a more cost-efficient rehabilitation of the CS. However, this is a highly challenging task that requires cooperation across the involved municipal sectors. While waiting for such a system to be put in place, a WWN owner can identify small, closed sub-catchments that drain into the CS. Within these areas, LID and GI can be implemented without having established an ISMS – as was the case at the site for A1 in this study.

In this study it is concluded that the implementation of A1 is most beneficial. A1 consists of three measures to address the existing challenges:

- LID measures consisting of disconnecting all downspouts and all impervious surfaces from the CS within a sub-catchment.
- GI measures consisting of infiltration trench and bioretention cells along public roads to reduce the risk of uncontrolled stormwater runoff.
- No-dig rehabilitation of the CS.

By retaining peak loads through LID and ensuring safe stormwater runoff through GI, the risk of damages from sewer overflow discharge, sewage backup and uncontrolled stormwater runoff is reduced. The combination of LID, GI and no-dig requires lower investments and is technically less challenging than open-cut methods. These measures can be installed faster, have less negative impact on the surroundings and reduce the climate footprint.

It is crucial to establish good cooperation routines and contracts between the project participants, i.e., WWN owners and private and public landowners, to ensure smooth operations during project implementation and long-term success for LID and GI measures.

When preparing this study, we invested much time obtaining the necessary data since the study went beyond traditional data collection for wastewater rehabilitation projects. We had to include several new parameters to obtain a basis for evaluating the costs and effects of LID and GI. The efficiency of the evaluation process can be increased by developing the map databases for the registration of rainfall-related damages, road drainage pipes, culverts that are crucial for stormwater runoff, risk and the possibility status of existing runoff pathways and depressions in the terrain.

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DATA AVAILABILITY STATEMENT

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

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