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Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway

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Abstract: Sewer networks represent high value in water infrastructure assets and it is important to develop and operate them by specified sustainable management. This paper presents the results of a sustainability analysis on the wastewater transport system of Trondheim, Norway, for future planning (2014–2040) from a metabolism-based performance analysis by the Dynamic Metabolism Model (DMM). The aim of this work is to demonstrate a methodology for comparing different pathways toward a sustainable management of wastewater systems. For this purpose, four intervention strategies 'infiltration and inflow reduction', 'increasing rehabilitation rate', 'extension of system regarding population growth', 'energy management' along with different combinations of them have been analysed. The results of this study may give some support to decision-makers in wastewater departments. In practice, to achieve strategic level planning of sustainable sewer asset management, it is vital to assess different aspects of sustainability and manage them in a comprehensive system.

Keywords: Sustainability, Urban Water Systems (UWS), sewer infrastructure asset management, Dynamic Metabolism Model (DMM)

Introduction

Urban water systems (UWS) are related to different aspects of sustainability such as social, economic, and environmental dimensions, which are 'triple bottom line' of the sustainability concept. Utilities usually have robust concepts of water quality, treatment efficiencies and cost-effectiveness; nevertheless, in recent years more attention has been given to broader sustainability aspects such as greenhouse gas emissions and life cycle environmental effects (Ashley *et al.*, 2008; Slagstad and Brattebø, 2014). Moreover, with regard to asset investments, the 'triple bottom line' approach of sustainability should be considered (Ashley *et al.*, 2008). The aim of this work is to demonstrate a methodology for comparing different pathways toward sustainable management of wastewater transport systems, which represent a high value in water infrastructure assets.

Urban water and wastewater infrastructure assets are undergoing aging and deterioration (Ana and Bauwens, 2010), due to lack of sufficient municipal investments in maintenance and rehabilitation (Rehan *et al.*, 2014). Functional efficiency and structural quality of sewer systems are the principal factors that ensure urban and industrial wastewater transport to treatment plants without infiltration and exfiltration (J. B. Ellis *et al.*, 2005). Management of infiltration and exfiltration in the urban sewer system is crucial in the long term to achieve good performance, which is a prerequisite for water infrastructural asset management and has significant environmental, social and economic impacts on cities (Beheshti, Sægrov and

Ugarelli, 2015). Moreover, the sustainable management of the water infrastructure should be considered in strategic long-term planning of UWS, which leads to economic and environmental achievements for society. These infrastructures present a high asset value and future generations will inherit the consequences of today's investments decisions (Marlow *et al.*, 2013). Unfortunately, this important issue in general has not been considered seriously until now and there are only few studies which have been carried out on social and environmental aspects of sustainability on UWS (Ludzia, Larsson and Aguayo, 2014).

Greenhouse gases (GHG) are released continuously during the installation phase, operation and maintenance phase and rehabilitation phase. However, more than 80% of these emissions happen during fabrication of pipelines (Strutt *et al.*, 2008; Venkatesh, Hammervold and Brattebø, 2009). Therefore, to reduce the amount of GHG emissions it is wise to keep current pipelines in the network by proper maintenance and rehabilitation plans, which is the main outcome of an efficient sustainable infrastructure management. There are different methodologies available for estimating the environmental impacts of water and wastewater systems, such as Strategic Environmental Assessments (SEA), Cost-Benefit Analysis (CBA), Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Environmental or Ecological Risk Assessment (ERA) (Finnveden *et al.*, 2009; Chen, Ngo and Guo, 2012).

SEA is a tool for integrated assessment of environmental aspects at a strategic level (Lee and Walsh, 1992; Salhofer, Wassermann and Binner, 2007). This method is defined as the structured and holistic procedure of assessing the environmental consequences in the initial phase of policies, plans and programs to assure they are properly addressed and are in line with economic and social concerns of decision-making (Nilsson *et al.*, 2005; Salhofer, Wassermann and Binner, 2007; Garfì *et al.*, 2011). The CBA method evaluates an urban system quantitatively from integrated economic and environmental aspects (Salhofer, Wassermann and Binner, 2007; Villarroel Walker *et al.*, 2014), with consideration of internal costs and external environmental and social impacts (Chen, Ngo and Guo, 2012). In this method, the flux of material, resource and energy into the system can be estimated as monetary revenue and expenditure changes (Villarroel Walker *et al.*, 2014). MFA is based on understanding and quantitative analysis of the flows, transformation and stocks of materials, energy and resources in a system specified in scope and time (Brunner and Helmut, 2004; Garcia-Montiel *et al.*, 2014). In UWS, MFA deals with the inflow of materials and energy to the water and wastewater networks, i.e. due to addition of pipelines and the rehabilitation rate. MFA is an effective initial monitoring method in UWS and its outcomes are a leading consideration for evaluating a system (Brunner and Helmut, 2004; Chen, Ngo and Guo, 2012). LCA is applied for evaluating the life cycle environmental impacts of the flows into a system, and has proven to be feasible in sustainability assessment of UWS in the last 20 years (Loubet *et al.*, 2014). Furthermore, ERA is a method for assessing the adverse impacts of environmental pollutions arising from human activities with a known uncertainty level (Oost, Beyer and Vermeulen, 2003). This method mainly evaluates site-specific chemical hazards in UWS (Chen, Ngo and Guo, 2012).

UWS can be analysed from a sustainability point of view by metabolism-based models. The approach is to assess and analyse the flow, conversion and process of resources in the concept of material, money and energy into the UWS to accomplish the mandatory requirements of the system in terms of water supply and sanitary transport at the required quantity and quality stages (Venkatesh, Sægrov and Brattebø, 2014). WaterMet^2 (WM2) developed at Exeter in the UK (Behzadian *et al.*, 2014), and the Dynamic Metabolism Model (DMM) developed at the Norwegian University of Science and Technology (Venkatesh, Sægrov and Brattebø, 2014) are two metabolism-based models for sustainability modelling and analysis of UWS, which are developed on the basis of MFA and LCA (Venkatesh *et al.*, 2017). These two mass-balanced-based models have been tested for analysis of energy consumption, emissions, costs and environmental impact of UWS in Oslo as a case study (Venkatesh *et al.*, 2017). UWS metabolism like other urban metabolic systems, is in interaction with other domains such as social, economic and environmental criteria (Behzadian and Kapelan, 2015), and these metabolism-based models give the opportunity to quantitatively investigate and document metabolism of UWS as a basis for sustainability analysis under different strategic scenarios and interventions for long-term planning.

In the current study, a sustainability analysis by DMM has been conducted on the wastewater transport system of Trondheim. The system consists of combined and separate sewer pipelines for transporting foul sewer and stormwater in addition to pumping stations. Other components of the wastewater system such as wastewater treatment plants (WWTP) are excluded from this study. This will require detailed analysis of the wastewater system hydraulic performance and respective detailed information of components in WWTP. They are therefore the subject of separate studies.

Methodology

The wastewater transport system has not been considered alone in previous sustainability studies. In this study, the metabolism of the wastewater transport system of the city of Trondheim in Norway has been investigated and assessed by the DMM. For this purpose, different scenarios and interventions have been defined as possible action requirements for improving the current system. Each of these scenarios involves a broad range of changes in economic and technological factors, and the environmental, functional and economic aspects of sustainability have been analysed and evaluated. The historical data of 2000–2013 have been used as the database of this study and predictions have been made for the period 2014–2040.

DMM

DMM is a mass-balance model, which was developed by Venkatesh et al. (2014) for UWS, within the European research project TRUST (TRansitions to the Urban Water Services of Tomorrow). The keyword ‘metabolism’ refers to inflow of materials and outflow of them in the concept of emissions and by-products from a system (Venkatesh, Sægrov and Brattebø, 2014). The aim of the development was to implement a complete systematic approach to the study of metabolism and environmental effects of resource flows in UWS, i.e. water flows, material and energy consumption, resource recovery, waste and emission flow (Appendix 8). This model offers an instrument for the investigation of possible future services, strategies and interventions in UWS (Venkatesh, Sægrov and Brattebø, 2014). Moreover, by using the DMM the UWS can be quantitatively analysed with regard to energy consumption, emissions, environmental impacts, economic and physical properties by annually-based performance indicators for the whole of the system and its subsystems (such as water distribution and wastewater transport) under different interventions toward future improvements (Venkatesh *et al.*, 2017).

The detailed concept of DMM has been presented by Venkatesh *et al*. (2014) for UWS. However, some important characteristics of this model are flexibility, simplicity and modifiability; nevertheless, it has its own shortcomings. The model has some simplicities that make it notable, such as a user-friendly interface in an MS-Excel-based model. Simplicity of this model can be both an advantage and a limitation. However, the main limitation of the DMM model is that it is a concentrated and lumped model in this version, which is based on general data of the system. The focus of this model is on investigating the impacts of long-term intervention strategies on the comprehensive view of the UWS for supporting decision-making (Venkatesh *et al.*, 2017). Therefore, DMM is a suitable tool for the initial analysis phase of strategic planning with requiring fewer data, while distributed models like WM2 can be used for more in-depth analysis requiring more detailed data (Venkatesh *et al.*, 2017). Moreover, this method has some limitations regarding uncertainty. There is always uncertainty when making assumptions for material flow rate and introducing new products and materials in the system, and it is very common that inflow, outflow and variations in materials and resources do not match (Brunner and Helmut, 2004).

In Trondheim, it is planned to add specified kilometer pipelines to the system every year and rehabilitate existing pipelines by a cured-in-place-pipe (CIPP) approach at a specific rate per year (Appendix 3 & 4). In this study, the flow of material and resources for the wastewater transport network has been considered and applied as inputs to the DMM model (Appendix 1 & 2). For calculation of pipeline material flow, some of the assumptions for transforming the pipeline length data to weights of the material are borrowed from the study that Venkatesh *et al*. (2009) has been carried out on MFA-LCA analysis of wastewater pipeline networks in Oslo, Norway. Furthermore, installation, rehabilitation, and maintenance and operation of wastewater pipelines are energy demanding and this aspect has been considered in this study.

Case system description

The city of Trondheim is the third largest in Norway with a population of 179,385 inhabitants in 2013 (Appendix 5). Prognosis from the Statistics Center Norway shows that Trondheim city will grow by around 30,000 new residents until 2025, and by 2040 there will be around a 30% increase in population compared with the year 2013 (Statistics Norway, 2015). In Trondheim, 50% of wastewater production is from households, which correlates to water consumption, and the remainder is from industry (Slagstad and Brattebø, 2014).

The wastewater transport system of Trondheim with average age of 30 years consists of about 1200 km in public and municipal sections. However, the oldest pipelines, which are still in use, are more than 100 years old. The wastewater network consists of pumping stations, combined and separate sewer pipelines for transporting foul sewage and stormwater for treatment to one of the WWTPs of Høvringen (HØRA) and Ladehammeren (LARA) before being released in Trondheim fjord (Figure 1(a)); 51.7% of the total length of the foul sewer network in Trondheim is separate, and the rest is combined. The length of the separate stormwater network in Trondheim at the end of year 2013 is 40% of the whole wastewater transport network. Moreover, there are 54 pumping stations in the wastewater transport system of Trondheim, of which three are for stormwater, 24 for foul sewer, and 27 for the combined system (Trondheim Municipality 2013). The water balance of wastewater and stormwater systems in Trondheim is shown in Figure 1(b), which illustrates the years 2009–2011.

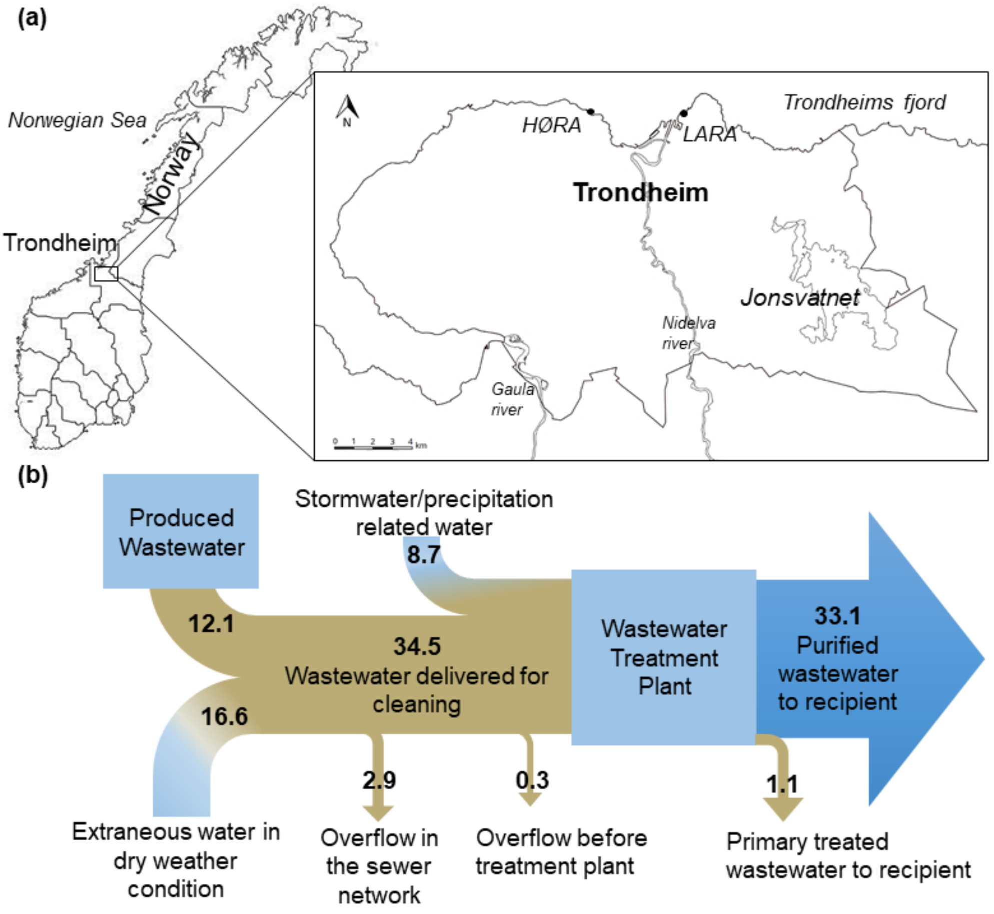

Figure 1. (a) The case study area. (b) Trondheim water balance 2009–2011 (million m^3/year) (Trondheim Municipality 2013).

This figure shows that the amount of infiltration and inflow (I/I) of extraneous water into the sewer system in dry weather conditions is about 46% of the water, which is delivered to the WWTP. It is a priority in the municipality to reduce this extraneous water, and the possible actions to handle this problem are:

- Increasing treatment capacity.
- Increasing the capacity of the wastewater transport system by separation of sewage and stormwater, installing detention basins and applying local stormwater solutions.
- Decreasing the amount of inflow and infiltration to wastewater transport system by spot repair and complete rehabilitation of sewer network.

In this study, some possible actions inside the wastewater transport system are considered by defining different scenarios and interventions in order to decrease the flaws and deficiencies and improving the current system.

Scenarios and interventions

One scenario is the combination of the actions of risk factors which influence the system in a specific way (Venkatesh, Sægrov and Brattebø, 2014). A risk factor is a specification, feature or aspect, which raises the likelihood of something undesirable happening. By identifying and understanding various risk factors, the related interventions and actions can be undertaken for preventing the unwanted consequences in the system.

According to the policies of the wastewater section of Trondheim municipality, the current plan is to improve the performance of the wastewater transport system and improve the stormwater management, in addition to having an energy management process. By analysing various risk factors, the need for new interventions arises. The risk factors that are considered in this study are population growth, asset deterioration, energy consumption, and climate change. A scenario can be a combination of two or more risk factors, which affect the sewer system functionality.

The ‘status quo’ presents the current condition of the network without considering any risk factors and the same population growth as in the prognosis (Appendix 5). Furthermore, a constant development of the wastewater network, as average network development and pipeline installation of 2005–2013, is assumed for period 2014–2040. In addition, the rehabilitation rate is the same as the master plan for Trondheim. Besides, a 10% reduction in water demand per capita until 2040 is assumed due to increasing inhabitants’ awareness of water usage and use of more water-saving facilities. Consequently, less water consumption will lead to less wastewater generation.

Table 1 demonstrates a general overview of risk factors and corresponding interventions, which are considered in this study for the wastewater transport system, according to discussions with experts in water and the wastewater section of Trondheim municipality. The black cells present the risk factors which are involved in each intervention.

Table 1. Risk factors and interventions of wastewater transport system.

Interventions	Risk factors			
	Population growth	Sewer asset deterioration	Energy consumption (Fossil fuel)	Climate change
a: Reduction of Infiltration and inflow		■	■	■
b: Increase of rehabilitation rate		■		

c: Extension of WW transportation network	▨			
d: Energy management			▨	
a+b		▨	▨	▨
a+c	▨	▨	▨	▨
a+d		▨	▨	▨
b+c	▨	▨		
b+d		▨	▨	
c+d	▨		▨	
a+b+c	▨	▨	▨	▨
a+b+d		▨	▨	▨
a+c+d	▨		▨	▨
b+c+d	▨	▨	▨	
a+b+c+d	▨	▨	▨	▨

Interventions

Various interventions can be implemented for the wastewater transport system. Some possible interventions which can be considered in this study arising from discussions with the Trondheim municipality, are listed below:

i. Intervention ‘a’: Reduction of infiltration and inflow (I/I)

Reduction in I/I of the non-sewer water to the system gradually, at a rate of 20% by the year 2040. Removing this water may add economic, environmental, and social benefits to the entire UWS. Spot repair is a solution for reduction of I/I to the wastewater network. The realistic number of repairs in this study is assumed to be 100 repairs per year. Spot repair can be supported by some high-tech tools such as fiber-optic Distributed Temperature Sensing (DTS) cables for localizing the exact I/I location in the sewer pipelines. The cost assumption for this purpose is about 1660 Euros per repair. This value adds to the operational expenses for each year.

ii. Intervention ‘b’: Increase of wastewater transport system rehabilitation rate

According to the master plan of Trondheim municipality, the rehabilitation rate, which is a combination of renovation and separation, for wastewater transport system in ‘status quo’ is around 5 km, which is 0.41% of the total wastewater network. It will increase gradually to 8 km (0.67%) by the year 2040 (Appendix 3). In this intervention, the rate of 1.6%, which is the reference rehabilitation rate in the Oslo municipality, is assumed for the sewer system for the whole study period. This rate is quite ambitious and is selected to visualize clearly the impact of extensive rehabilitation on the environment. It is assumed that this increase in rehabilitation rate will decrease the I/I to the wastewater network by a rough estimation of 15% until the year 2040. Having detailed information regarding the size and length of pipelines, the corresponding ratio for the year 2013 is used for the whole of the study period.

The cost assumption for rehabilitation of each kilometer of pipeline is about 440 Euros/m for renovation and 880 Euros/m for separation and replacement. This value has been considered in this study, for the additional rate of rehabilitation, which has not been considered in the current rehabilitation plan of Trondheim.

iii. Intervention ‘c’: Extension of wastewater transport network

In this study, it is assumed that a constant development average of 2005–2013 for the entire study period is the ‘status quo’. However, population growth may require a different extension of the sewer and stormwater networks. In this intervention, extension of the wastewater network has been considered proportional to the population growth rate. The expansion of the system as ‘status quo’ is higher than when considered based on population growth (Figure 2).

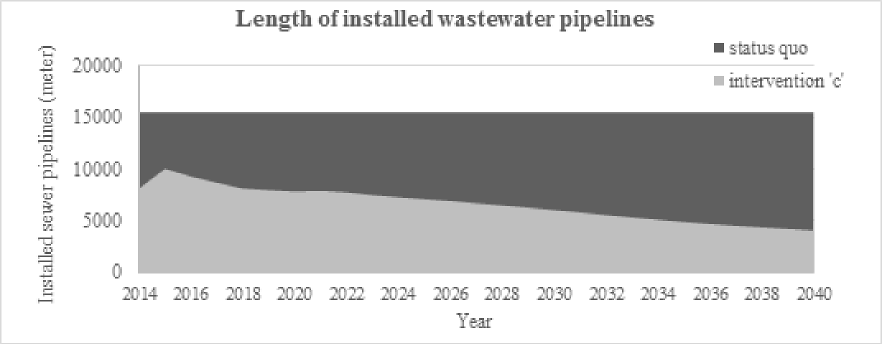

Figure 2. Extension of the sewer network based on population growth in intervention ‘c’ versus constant development as average 2005–2013 in ‘status quo’.

The existing system is generally overdesigned and possesses extra capacity for wastewater transport, especially in the combined sewers, which cope well in extreme events. This capacity can be utilized in city expansion, since the focus is on reduction of I/I into the sewer system and separation of combined networks. Also, this can be supported by blue-green solutions for stormwater management.

iv. Intervention ‘d’: Energy management

From an energy point of view, it is considered desirable to reduce energy consumption by a reasonable estimate of 20% by 2040 due to using more electricity instead of diesel and fossil fuels, automation/optimization of pumping stations, using more no-dig technology in rehabilitation of the network, and using more electric vehicles and instruments. To fulfil this purpose, an investment of 0.11 million Euros per year is assumed.

The combination of a+b, a+c, a+d, b+c, b+d, c+d, a+b+c, a+b+d, a+c+d, b+c+d, and a+b+c+d are also considered in this study and the most powerful combinations are presented in the results.

Results and Discussion

The per capita indicators, which are investigated in this study, are listed as below:

- GHG emissions per capita
- Total energy consumption per capita
- Length of pipeline per capita
- Wastewater treated per capita
- Operation and maintenance expenses per capita
- Capital expenditure per capita

Table 2 demonstrates the percentages of changes of selected indicators in 2040 for the wastewater transport system of Trondheim, which are modelled in DMM, compared with ‘status quo’ in the same year. In all the changes, a negative value is desirable.

Table 2. Changes of selected indicators in 2040 (in percent) for Trondheim wastewater transport system in comparison with ‘status quo’.

Indicators		**Environmental**		**Physical & Functional**		**Economic**	
		GHG emissions per capita (kg CO2-eq per cap/y)	Total energy consumption per capita (kWh per cap/y)	Length of pipelines per capita (km per cap)	Wastewater treated per cap per year (m^3 per cap)	O&M expenses per capita (Euros per cap/y)	Capital expenditure per capita (Euros per cap/y)
Increase desirable? (Y/N)		N	N	Y-N	N	N	Y-N
Interventions in 2040	a	-0.3	-0.55	0.0	-9.4	1.01	0.0
	b	29.9	24.9	12.1	-6.7	3.11	254.3
	c	-40.1	-37.6	-13.8	0.0	-4.6	-44.2
	d	-4.3	-5.0	0.0	0.0	0.08	0.0
	a+b	29.5	24.4	12.1	-16.1	4.11	254.3
	a+c	-40.4	-38.2	-13.8	-9.4	-3.6	-44.2
	a+d	-4.6	-5.6	0.00	-9.4	1.09	0.00
	b+c	-10.2	-12.6	-1.6	-6.7	-1.5	238.6
	b+d	25.6	19.9	12.1	-6.7	3.2	254.3
	c+d	-44.4	-42.6	-13.8	0.00	-4.56	-44.2
	a+b+c	-10.5	-13.2	-1.63	-16.1	-0.52	238.6
	a+c+d	-44.7	-43.2	-13.8	-9.35	-3.55	-44.2
	a+b+d	25.3	19.4	12.1	-16.1	4.19	254.3
	b+c+d	-14.5	-17.6	-1.6	-6.7	-1.45	238.6
	a+b+c+d	-14.8	-18.2	-1.6	-16.1	-0.44	238.6

It is clear from Table 2 that interventions ‘c’, ‘a+c’, ‘c+d’, ‘a+c+d’ present better results in all indicators especially in decreasing GHG emission and energy consumption per capita. Interventions ‘b+c’, ‘a+b+c’, ‘b+c+d’ and ‘a+b+c+d’ present rather good results compared with ‘status quo’ in 2040. The overweighting intervention here is intervention ‘c’, which is an extension of the system by population growth rate. This intervention represents a lower degree of network extension and construction work than ‘status quo’, which causes less resource usage and therefore more environmental and economic benefits.

Interventions ‘b’, ‘a+b’, ‘b+d’ and ‘a+b+d’ do not demonstrate good results in the wastewater transport system, regardless of decreasing the amount of wastewater, which is delivered to the treatment plant. The overweighting intervention here is ‘b’. In intervention ‘b’, increasing the rehabilitation rate and separation of the system adds more construction work to the network and therefore, the environmental and economic results are not desirable in the analysis of only a wastewater transport system. While it adds significant benefits to the environment by reduction of CSO and decreasing pollution in recipient. Moreover, decreasing the amount of I/I, which is delivered to WWTP, increases environmental advantages by less chemical- and energy-usage. However, these results are not considered here.

Interventions ‘a’, ‘d’ and ‘a+d’ demonstrate low falls in results compared with ‘status quo’. However, intervention ‘a’ adds outstanding advantages to CSO and WWTP by a reduction of I/I.

Figure 3(a) demonstrates the changes in GHG emissions for different single interventions during the modelling period until 2040. In addition, total energy consumption per capita follows the same pattern as changes in GHG emissions in different interventions.

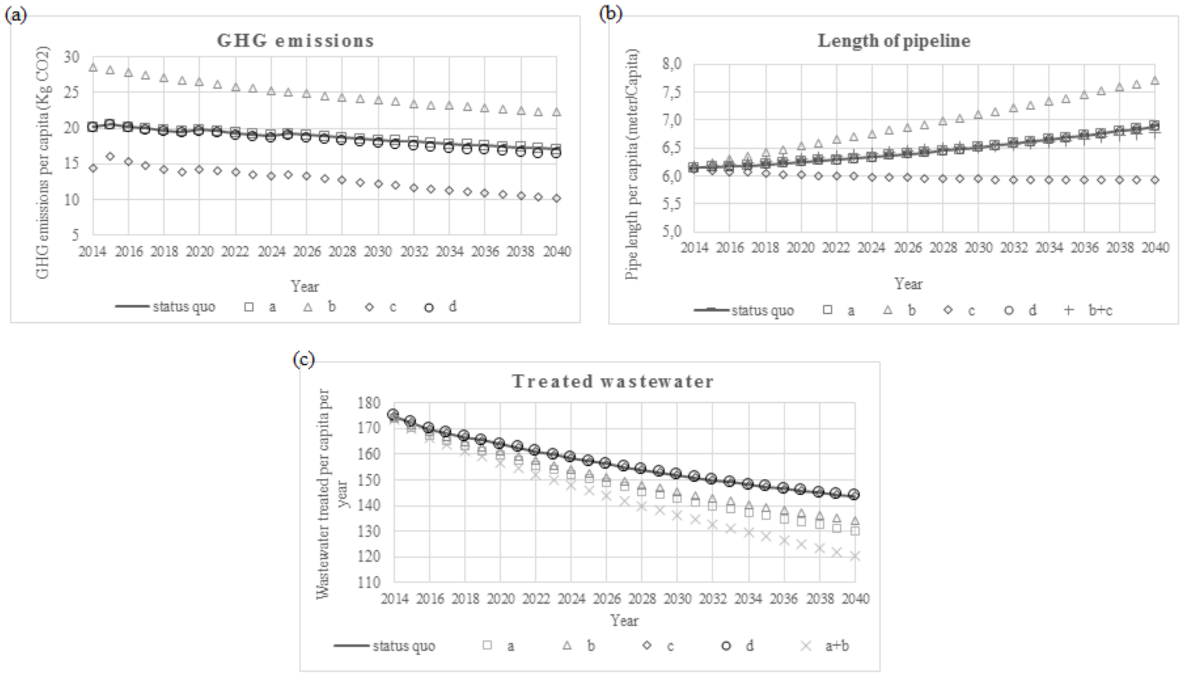

Figure 3. (a) Changes in GHG emissions per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’). (b) Changes in length of pipeline per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’, ‘b+c’). (c) Changes in wastewater treatment volumes per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’, ‘a+b’).

From a physical point of view, as illustrated in Figure 3(b), the lengths of network per capita in interventions ‘a’ and ‘d’ are not changed compared with the ‘status quo’. In interventions ‘a’ and ‘d’ a constant rate as ‘status quo’ is assumed for the network growth until 2040. The network in intervention ‘b’ and its combinations with interventions ‘a’ and ‘d’, which are ‘a+b’, ‘b+d’ and ‘a+b+d’, has greater length because of increasing the rehabilitation length and increasing the length of the separate wastewater network. However, the length of the network in intervention ‘c’ and its combinations with interventions ‘a’ and ‘d’ is the shortest between all interventions. In intervention ‘c’ the focus is on developing the system by population growth rate. The combination of ‘b’ and ‘c’ and their combinations with interventions ‘a’ and ‘d’ illustrate an increase until year 2032 and then gradually decreases compared with the ‘status quo’.

Treated wastewater volume per capita decreases in the interventions, which are combinations of ‘a’, ‘b’ or both of them due to decreasing the I/I to wastewater pipelines. Intervention ‘a+b’, and its combination with other interventions illustrate the largest decrease in the treated wastewater per capita. The interventions ‘a’ and ‘b’ have the next most significant falls, respectively. The treated wastewater in interventions ‘c’, ‘d’, and ‘c+d’ remain the same as ‘status quo’, as well as decreasing significantly compared with year 2013 in all interventions because of the basic assumption of reduction of I/I to the sewer system by 2040 in ‘status quo’ (Figure 3(c)).

With regard to economic analysis, it is important to clarify the capital expenditure and operational and maintenance (O&M) expenses per capita. Capital expenditure refers to depreciation and interest payments, while the inputs of O&M expenses are energy, chemicals, maintenance and salaries. In this study, in interventions ‘b’ and ‘c’ the focus is on capital expenditure, due to depreciation cost of new pipelines in the system. However, in ‘a’ and ‘d’ the O&M expenses are considered with regard to extra maintenance and energy expenses. Furthermore, O&M expenses are also affected in ‘b’ and ‘c’ because of energy demand for installing and removing pipelines in the system. Capital expenditure per capita is not affected in ‘a’, ‘d’ and ‘a+d’. However, it decreases in intervention ‘c’, and intervention ‘b’ illustrates the largest increase; then, as presented in Figure 4(a), intervention ‘b+c’ shows an increase, which is less than the increase in intervention ‘b’. It is worth mentioning here that Figure 4(a) is not a smooth graph due to data on the economy from Trondheim municipality, which is used as the database of this study and is presented in ‘status quo’ (Appendix 7). O&M expenses per capita fall the most in intervention ‘c’ because of installing fewer pipelines than ‘status quo’. Other single interventions show increase in O&M expenses in comparison with ‘status quo’, while intervention ‘b’, ‘a’ and ‘d’ show the highest to lowest increases respectively. The highest O&M expenses in intervention ‘b’ is because of increasing rehabilitation rate which imposes high energy, salary and maintenance expenses (Figure 4(b)).

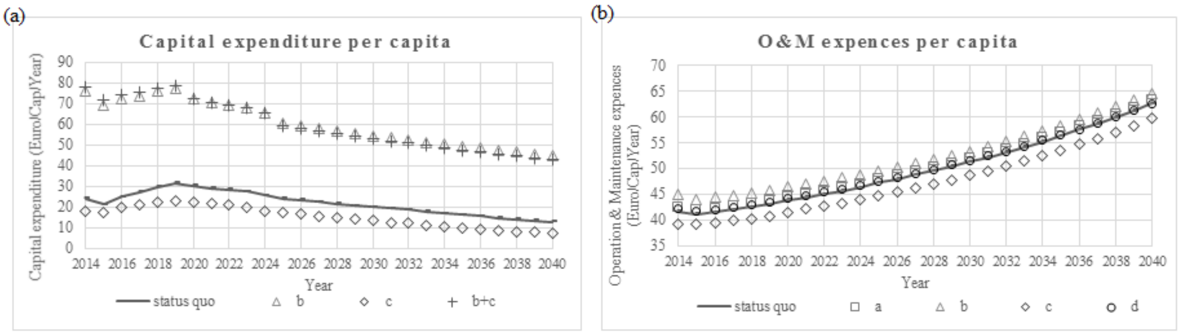

Figure 4. Changes in (a) capital expenditure, and (b) operation and maintenance expenses per capita.

The results of this study are based on the analysis of different interventions in the wastewater transport system of Trondheim, and the CSO and WWTP are not considered in this study. Furthermore, future interventions and assumptions of influx of material, energy and resources into the system are always followed by uncertainty, which is not considered in this study.

Conclusion

In the present study, the wastewater transport system of the city of Trondheim is analysed from a sustainability point of view by the dynamic metabolism model (DMM). The focus of this research is on environmental, energy, physical, and economic aspects of sustainable wastewater infrastructure management in the strategic planning period 2014–2040, based on the historical database 2000–2013. The main approach of this study is to analyse the impacts of different risk factors on the wastewater transport system and compare them with 'status quo' with a constant development of the wastewater network. With this aim, four interventions: 'a' (infiltration and inflow reduction), 'b' (increasing rehabilitation rate), 'c' (extension of system regarding population growth) and 'd' (energy management) along with different combinations of these interventions have been analysed. Based on the obtained results, the overall conclusions are as follows:

Interventions of reduction of I/I (a), and energy management (d), and combinations of them (a+d) demonstrate low falls in results compared with 'status quo'. These interventions also do not affect other interventions significantly in their combinations. However, by reduction of I/I in intervention 'a', outstanding advantages will accrue to CSO and WWTP by reducing wastewater volume. Nevertheless, the results of this study do not demonstrate the comprehensive effects on the whole wastewater system.

Intervention 'b' presents the need for increasing the performance of the system by increasing the rehabilitation rate and separation of the network. This intervention does not demonstrate good results in the wastewater transport system for the selected level of rehabilitation (1.6%), regardless of reducing the amount of wastewater delivered to the treatment plant. It has also significant benefits on CSO and WWTP, which is outside the scope of this study.

Intervention 'c' is extension of the network by population growth rate, which is actually lower than the extensions of recent years ('status quo'). In the existing system extra space is supplied for wastewater and stormwater transport. Additionally, for stormwater systems, blue-green solutions can reduce the need of extra flow capacity, and this is recognized in intervention 'c'. This intervention and its combinations with 'a', 'b' and 'd' present good results in all indicators especially in decreasing GHG emissions and energy consumption.

The energy management intervention (d) does not show any remarkable changes in results compared with 'status quo'. This intervention represents automation/optimization of pumping stations, using more trenchless and no-dig technology in rehabilitation of the network and using more electric vehicles and instruments. By such measures, cities can achieve better energy management and significant reduction in diesel energy consumption. This will have major impact on the sustainable management of the wastewater system.

The results of this study provide some evidence to decision-makers in the wastewater departments of Trondheim and other cities. For future developments, which are based on various climatic, socioeconomic and anthropogenic scenarios, the fulfilment of assumptions is strongly associated with future conditions and, therefore, uncertainty plays a relevant role, and reliability of the outcomes can be affected significantly (Freni, Mannina and Viviani, 2012). Therefore, it is worth taking into account uncertainty analysis in decision-making. Moreover, it is important to consider the whole system for final analysis and decision-making. This can lead to long-term sustainable plans and management in a wastewater transport system by having more focus on the environmental feature of sustainable sewer asset management besides the economic, physical, functional and social aspects.

Discussion of system boundaries

We didn't consider CSO and WWTP in this study because of lack of data. However, the importance of considering these elements of wastewater system is not negligible and should be considered in the future research.

Supplementary data

The supplemental material for this paper is available online at https://doi.org/10.1080/1573062X.2017.1363253.

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SUPPLEMENTARY DATA

Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway

Maryam Beheshti & Sveinung Sægrov

DMM was applied to investigate and assess sustainability from environmental, physical, functional and economic aspects on the wastewater transport system of Trondheim in the period 2014-2040, based on historical database 2000-2013. The flow of material and resources to wastewater transport network was exploited as DMM model inputs (Appendix 1 & 2). Rehabilitation of the sewer pipelines in Trondheim consists of renovation of the existing pipelines by a cured-in-place-pipe (CIPP) technique and separation of them by adding new pipeline to the network. The inflow of material into the sewer network according to rehabilitation plan of Trondheim was considered in this study (Appendix 3 & 4). Moreover, the historic energy consumption data in wastewater transport system was used as model input. Population prognosis of Trondheim until 2040 was considered according to statistic center of Norway. Population of Trondheim is rising and according to prognosis from statistic center of Norway, Trondheim municipality will grow by around 60 000 new residents until 2040, which is 33% increase in population in comparison with year 2013 (Appendix 5). Furthermore, the energy consumption of pipeline rehabilitation, maintenance and operation was considered (Appendix 6). The economy input data of this study has been extracted from the annual investment plan of wastewater transport system of Trondheim municipality for the period 2013-2040 (Appendix 7).

Appendix 1: Pipeline data

It is necessary to acquire detailed information on characteristics of the pipeline network in Trondheim for modelling sustainability in DMM. In classifying the pipelines, diameters less than 249 mm are considered as small, between 250 mm and 499 mm are considered as medium-size and bigger than 500 mm are large pipelines. Based on available pipeline data the average percentage of pipelines with different sizes have been calculated for each year. Afterwards, according to the total length of installed pipelines in the system in each year, detailed average length of each size was calculated. In this study the average wastewater pipeline installation values from 2005-2013 were assumed as input values for the whole of prediction period 2014-2040 in status quo.

Table S1. Average length and percentage of installed and registered pipelines (2005-2013).

size	small	medium	large
Average percentage (%) (2005-2013)	52,0 %	33,3 %	14,7 %
Average length (m) (2005-2013)	7886,4	5048,9	2236,2

Appendix 2: Pipe material

The materials of Trondheim wastewater network by the end of the year 2013 is presented in figure below. As it is illustrated in this figure, the main part of the system is concrete pipeline with 81% of the total pipelines. PVC and PP pipelines are in the second score by 10% ratio. In addition, Table below presents average material distribution of installed pipelines in Trondheim based on their functionality in 2005-2013.

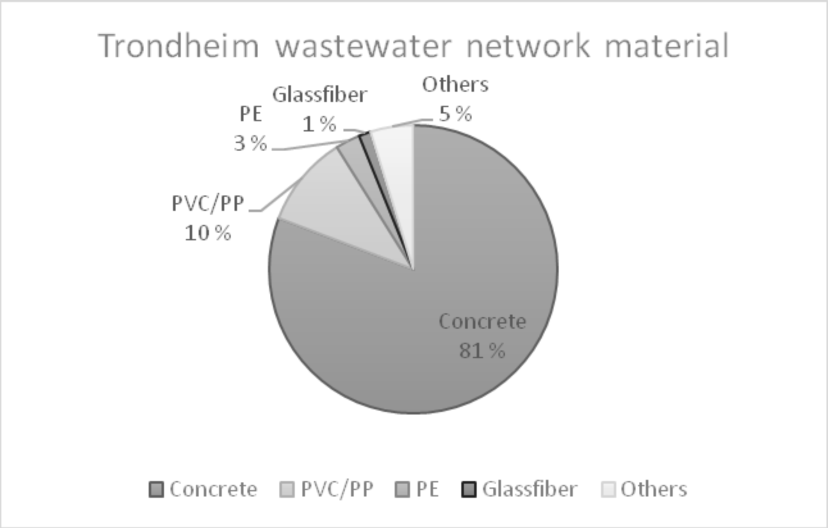

Figure S1. Wastewater pipeline material of Trondheim municipality at the end of 2013.

Table S2. Average distribution material of installed pipelines (2005-2013).

	wastewater				stormwater				Combined sewer			
Average	Concrete	PVC	PE	PP	Concrete	PVC	PE	PP	Concrete	PVC	PE	PP
2005-2013	36.8 %	52.5 %	9.4 %	1.3 %	59.4 %	36.0 %	3.7 %	0.9 %	62.4 %	16.6 %	17.4 %	3.6 %

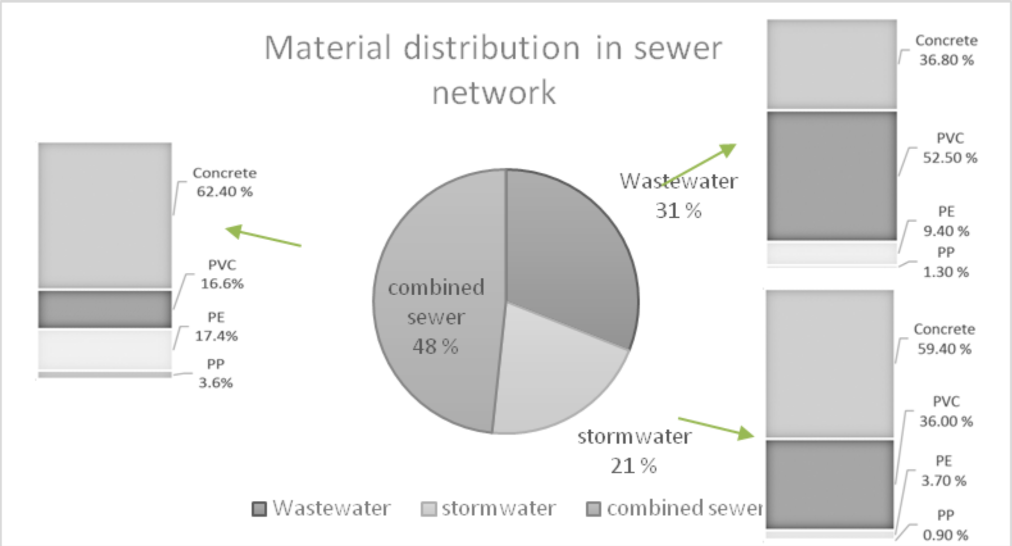

Figure S2. Average distribution material of installed pipelines (2005-2013).

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Appendix3: Renovation and replacement

Rehabilitation is a combination of renovation and replacement. The general rehabilitation objectives for Trondheim municipality are:

- minimum 5 km sewer pipelines per year in period 2013-2014
- minimum 6 km sewer pipelines per year in period 2015-2019
- minimum 7 km sewer pipelines per year in period 2020-2024
- Around 8 km sewer pipelines per year in 20-30 years

The percentage of rehabilitation length in 2013-2014, according to this plan is about 0.41% of total wastewater transport network. For rehabilitation purposes, a polyester liner is utilized as CIPP. This rehabilitation technique focuses on tightening and strengthening the existing pipelines on site with trenchless and no dig solutions. In Trondheim, renovation proportion by CIPP is currently about 1/3 of all sewer network rehabilitation and the other 2/3 is replacement of combined pipelines with separated ones.

According to Trondheim municipality in 2013, renovation is applied when:

- Combined system should be retained.
- Combined system assumed to lie minimum 20-30 years ahead.
- The renovated combined pipeline can serve as wastewater pipe in a future separate system.

However, in the case of replacement of combined pipelines by digging methods, it is important to change it to separate pipelines. In separation, the current pipeline remains as wastewater pipeline and a new stormwater pipeline is introduced to the system.

Based on the average ratios of pipeline size and length between 2005-2013 and objectives for pipeline rehabilitation lengths in future, detailed estimations for rehabilitation length for different sizes of pipelines in the study period has been made. Moreover, in order to find the influx of polyester to sewer pipelines by renovation methods, it is assumed a nominal diameter for each group of small, medium and large pipelines (small: 150, medium; 300, and large: 550 mm).

Appendix 4: Polyester for CIPP rehabilitation

Chosen Thickness of Polyester coating in a CIPP – 7.6 millimetres with a specific density of 1380 kilograms per cubic meter.

Appendix 5: Population change

Net migration to Trondheim is rising and is expected to continue. Prognosis from Statistics Center Norway shows that Trondheim municipality will grow with around 30000 new residents until 2025 compared with population of 2013. By 2040, there will be around 30% increase in population in comparison with year 2013 (Statistics Norway 2013).

Table S3. Annual percentage increases in population growth prognosis of Trondheim considered for the modelling (Statistics Norway 2013).

Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year
2014	1.39%	2021	1.19%	2028	0.91%	2035	0.74%
2015	1.56%	2022	1.14%	2029	0.91%	2036	0.65%
2016	1.48%	2023	1.13%	2030	0.90%	2037	0.64%
2017	1.46%	2024	1.11%	2031	0.77%	2038	0.64%
2018	1.44%	2025	1.26%	2032	0.76%	2039	0.64%
2019	1.42%	2026	0.93%	2033	0.76%	2040	0.63%
2020	1.4%	2027	0.92%	2034	0.75%		

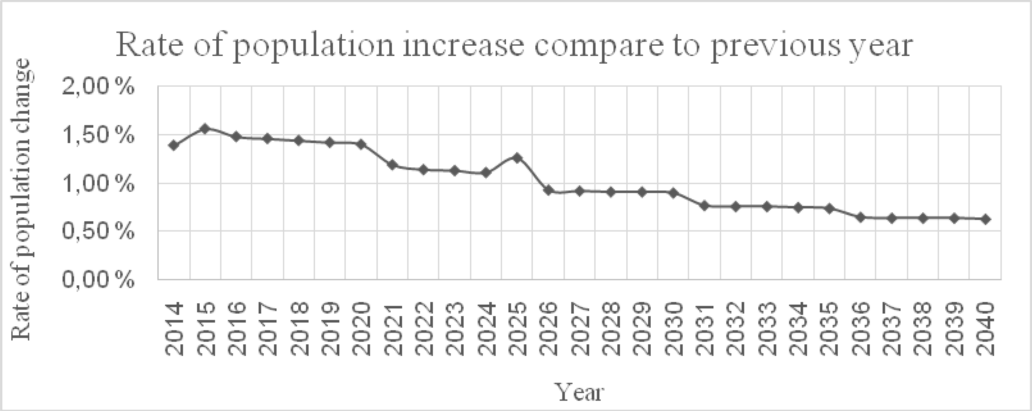

Figure S3. Annual percentage increases in population growth prognosis of Trondheim considered for the modelling (Statistics Norway 2013).

Appendix 6: Energy consumption

Diesel is consumed in installation, operation and maintenance (O&M), rehabilitation and retirement process of pipelines in water and wastewater networks. The DMM model has some assumptions for specific energy consumption for all of these activities on pipelines in the network based on different size categories. Furthermore, the historic energy consumption data in wastewater transport system was extracted from Trondheim municipality database.

Table S4. Diesel Consumption (sourced from the Appendix in Venkatesh (2011)).

Small-size pipelines	1 litre per metre
Medium-size pipelines	1.5 litre per metre
Large-size pipelines	2 litres per metre

Appendix 7: Economy

The economy input data of this study has been extracted from the annual investment plan of wastewater transport system of Trondheim municipality for the period 2013-2040. The exchange rate of Norwegian Kroners (Nok) to Euro has been considered 0.11 in this study (Source: www.xe.com, March 2015).

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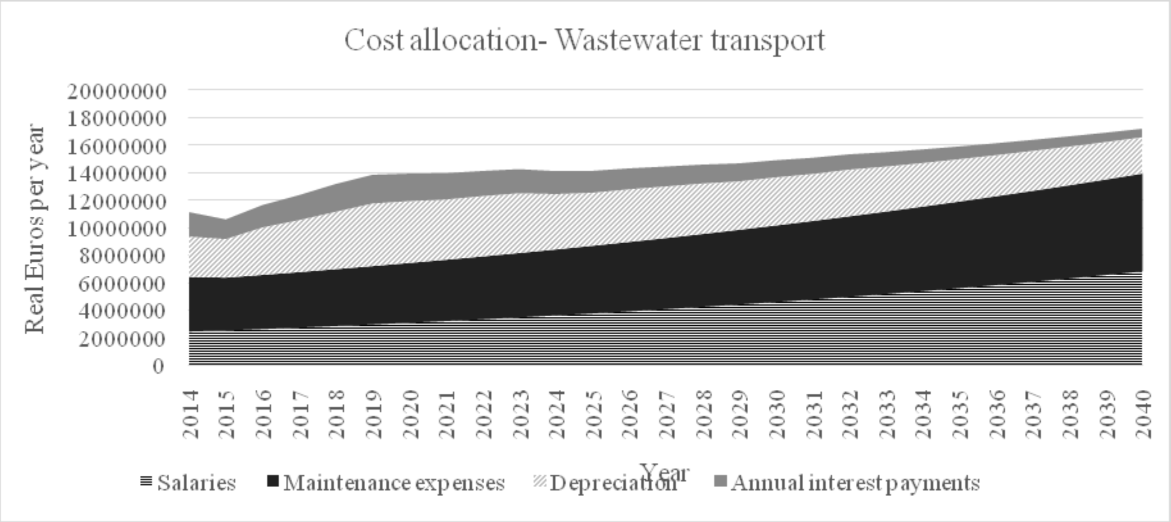

Figure S4. Cost allocation of wastewater transport system Trondheim for 2013-2040 (Trondheim Municipality; 2013).