TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

Oslo Case Study Report

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Abstract

The report presents the WaterMet^2 Oslo model, built based on the urban water system of Oslo which faces water scarcity problems for a 30-year planning horizon starting from year-2011. In order to cope with these challenges, 28 intervention strategies, each of which comprises either simple or complex intervention options are defined. They are examined and compared with each other in three stages against some quantitative criteria quantified by the WaterMet^2 model. The quantitative criteria include water supply reliability, average annual leakage, total capital cost, average annual cost and average annual GHG emissions; and the qualitative criteria are health risks, social acceptance and company acceptance. All the intervention strategies are finally ranked by using the Compromising Programming MCDA method. Two types of rankings are performed including one with quantitative criteria only and the other one with both quantitative and qualitative criteria. The ranking of the results shows some potential and promising strategies. However they cannot be fully trusted currently for any real decision-making without further development and validation for multiple future scenarios and risk type criteria.

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1 Introduction

This report presents the application of the first version of the WaterMet^2 model on the Oslo case study in WP34. The WaterMet^2 model will also be used for the development of risk assessment models in WP32, and will become a part of the decision support system for the long-term planning of UWS in WP54.This report is one of the outcomes of work done in WP33 and WP34 and has been prepared based on the earlier recommendations made in the Scoping Report (Brattebø et al. 2011), the relevant risk modelling concepts provided by SINTEF (WP32), the functional requirements report (Behzadian et al. 2012) and WaterMet^2 conceptual model report (Behzadian et al. 2012). The report focuses on the water supply side of Oslo's urban water system (UWS) which faces water scarcity problems and examines different intervention strategies under a specific scenario to cope with these challenges. The evaluation criteria quantified by using the WaterMet^2 model will be calculated for a 30-year planning horizon starting from year 2011.

The rest of this report will address and describe the following key elements. The Oslo case study is first outlined by describing the main components of the water supply side of the UWS. In the next section, potentially feasible and applicable intervention strategies to Oslo UWS during the planning horizon are described along with the relevant assumptions and outcomes. Then, the evaluation criteria which need to be quantified for the case study and the analysis scenario under which all the intervention strategies are assessed are presented. The results of the application of intervention strategies on WaterMet^2 Oslo model are then presented and analysed. Finally, the key messages are summarised.

2 Oslo Case Study Outline

2.1 Problem description

The main water supply components of Oslo UWS which will be modelled by the WaterMet^2 model comprise water resources, trunk mains, Water Treatment Works (WTWs) and pipelines. The related characteristics of the components and their interconnections in the Oslo city are described in the following sections.

2.1.1 Raw water resources

Two main raw water resources are currently available to supply fresh water to Oslo city-Maridalsvannet Lake (located in the north with 90% supply) and Elvåga Lake (located in the east with 10% supply) which are shown in Figs. 1 and 4. For further details of the existing systems and potential water resources, please refer to the documents ‘Rough Analysis of Alternatives’ and ‘Forecast of Water Usage in the Future in Oslo’ and ‘Water Treatment Plant Bulletin’ (Oslo Water 2011a and b). In addition to these existing resources, two potential (new) raw water resources for Oslo city are envisaged in the future as the Holsfjorden Lake (west of Oslo) and the Glomma River (east of Oslo) which are schematically depicted in Fig. 4. Unlike the existing water resources, the new raw water resources have an unlimited annual capacity of raw water.

As the catchment areas of the two existing water resources are limited, the water supply of Oslo city can be affected by the annual water inflows into these water resources. The time series of the inflows into each source as well as the associated water withdrawals between 1900 and 2010 are provided in Figs. 2 and 3. Note that the minimum environmental water demands of downstream rivers were subtracted from the inflows, and hence, these net inflows are fully assigned to the water supply in Oslo. For the purpose of this report, the monthly time series of the last 30 years (i.e. between 1981 and 2010) are selected as time series of inflows into the existing water resources during the 30 year planning horizon.

The specifications of these water resources which will be used in the waterMet^2 model are given in Table 1. As unlimited water is available from the two new raw water resources, high values can be assumed for capacity, initial volumes and inflows for these resources when modelling by WaterMet^2.

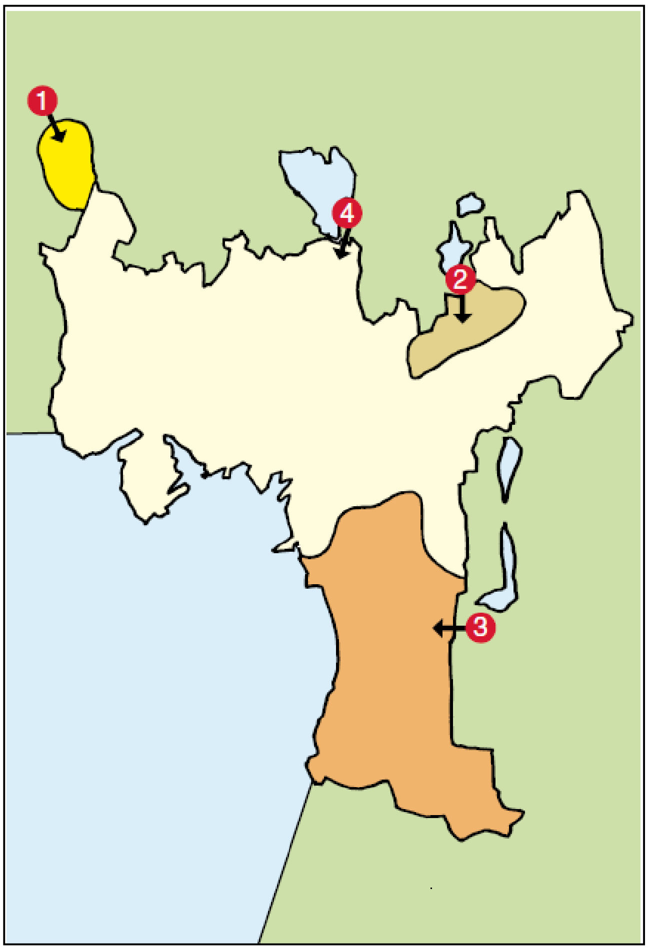

Figure 1: Schematic diagram of Oslo case study and the location of the existing water resources and WTWs; arrow no. 3 representing Elvåga Lake and Skullerud WTWs and arrow no. 4 representing Maridalsvannet Lake and Oset WTWs

Table 1: Raw water resources in Oslo UWS model

Name of raw water resource	Water resource ID	Status	Electricity (kWh/m^3)	Fossil fuel (kg/m^3)	Capacity (m^3)	Initial volume (m^3)	Operational cost (Euro/year)
Maridalsvannet Lake	1	existing	0	0	60,000,000	30,000,000	0
Elvåga Lake	2	existing	0	0	13,800,000	6,900,000	0
Holsfjorden Lake	3	new	0	0	Unlimited	-	0
Glomma River	4	new	0	0	Unlimited	-	0

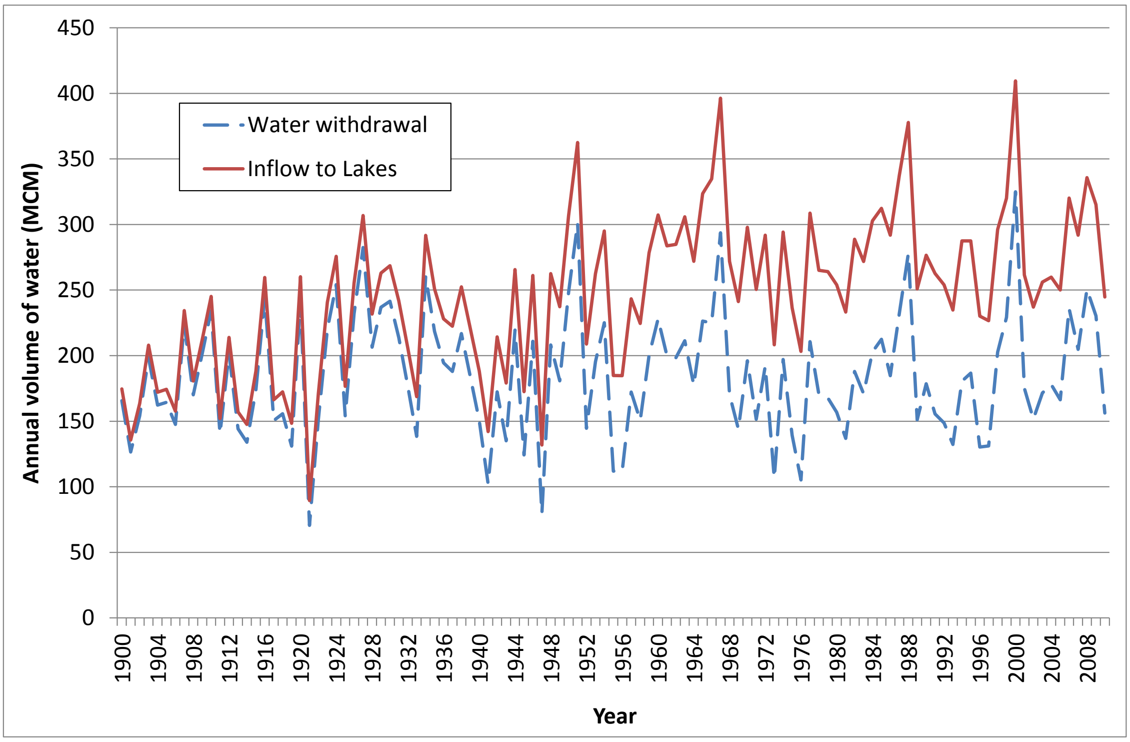

Figure 2: Annual volume of water inflows to, and withdrawal from, Maridalsvannet and upstream lakes between 1900 and 2010

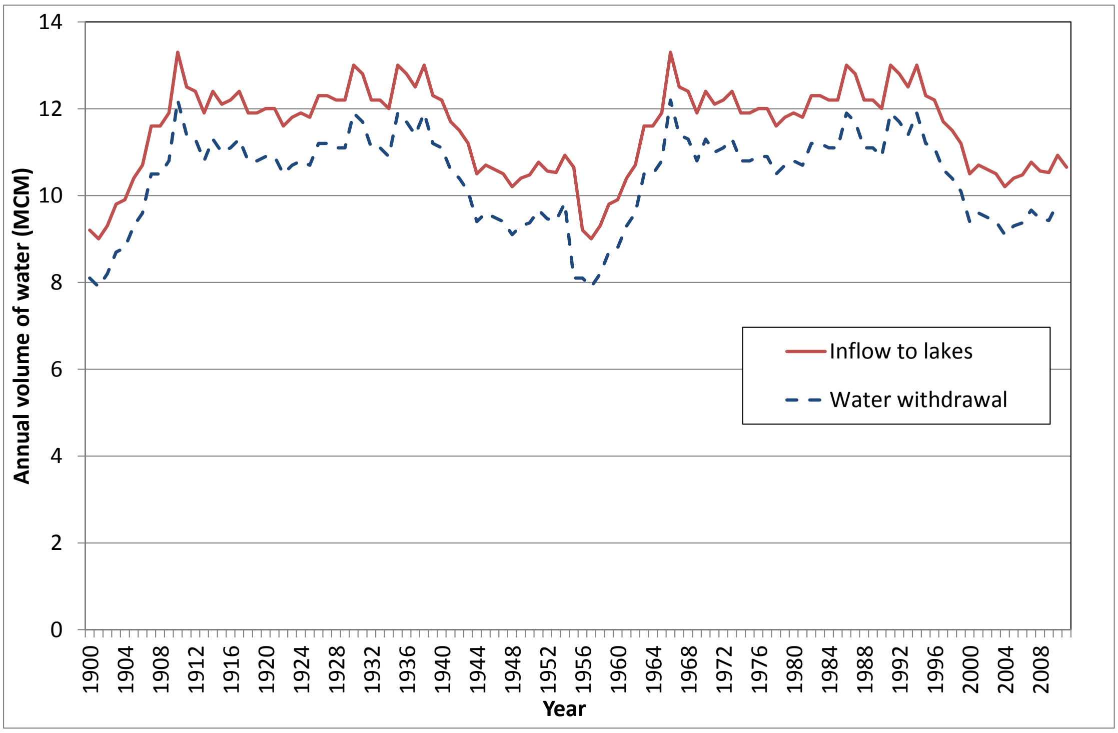

Figure 3: Annual volume of water inflows to, and withdrawal from, Elvåga and upstream lakes between 1900 and 2010

2.1.2 Water Treatment Works

The existing Oslo UWS has two WTWs which are directly supplied from the existing raw water resources (see Figs. 1 and 4). They are: (1) Oset WTWs fed by the Maridalsvannet Lake (located in the northern part of Oslo) and (2) Skullerud WTWs fed by the Elvåga Lake (located in the eastern part of Oslo). When supplying water from new water resources in the future, three WTWs will be built in order to comply with the developed UWS, which are shown in Fig. 4. They are: (1) WTWs for the treatment of raw water withdrawn from the Holsfjorden Lake (WTWs 3); (2) WTWs for the treatment of raw water abstracted from the Glomma River (WTWs 4); (3) a new Oset WTWs for the treatment of raw water from either the Maridalsvannet Lake or the Holsfjorden Lake (WTWs 5). The specifications of these WTWs which will be used by the WaterMet^2 model are given in Table 2. In addition, the specifications of the trunk mains connecting raw water resources to WTWs in Oslo UWS are given in Table 3 and shown in Fig. 8 for the existing system and Figs. 9-12 for the proposed new system with additional water resources. Note that two trunk mains are introduced in this Table for WTWs#5 since two water resources can feed this WTWs (see also Fig. 12).

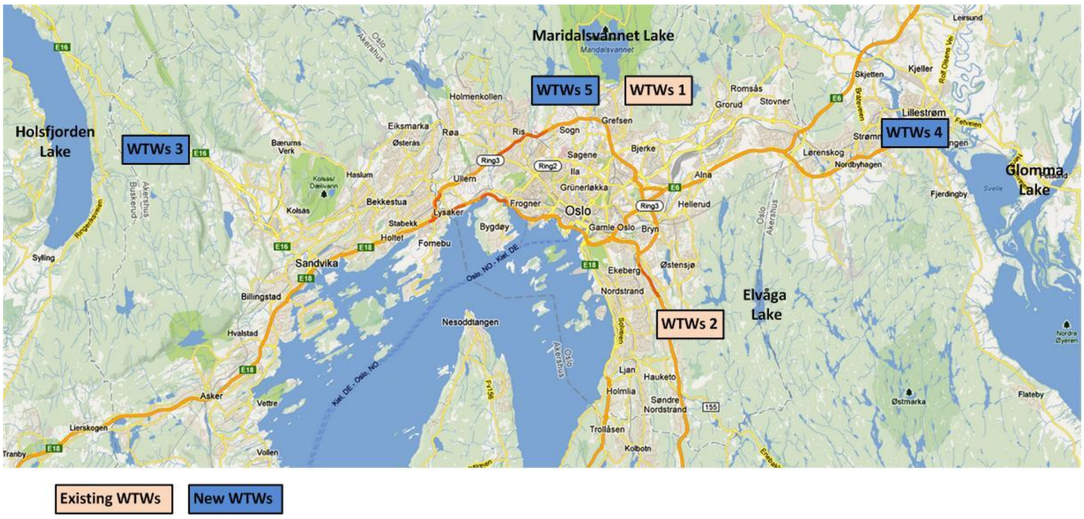

Figure 4: General layout of the existing and new WTWs and water resources in Oslo case study

Table 2: WTWs in Oslo UWS model

Name of WTWs	WTWs ID	Status	Capacity (m³/day)	Electricity (kWh/m³)	Fossil fuel (kg/m³)	Operational cost (Euro/year)	Chemicals cost (Euro/m³)	Sludge generation (kg/m³)
Oset	1	existing	370,000	0.343	2.30	23,220,000	0.0042	0.091
Skullerud	2	existing	43,200	0.343	2.30	2,580,000	0.0042	0.091
Holsfjorden Lake	3	new	691,200	0.343	2.30	48,302,100	0.0042	0.091
Glomma river	4	new	691,200	0.343	2.30	48,302,100	0.0042	0.091
New Oset	5	new	345,600	0.343	2.30	23,220,000	0.0042	0.091

Table 3: Trunk mains in Oslo UWS model

Name of trunk mains	*Status*	*Capacity (m^3/day)*	*Leakage (%)*	*Electricity (kWh/m^3)*	*Fossil fuel (kg/m^3)*	*Operational cost (Euro/year)*
WTWs1-Resource1	existing	1,036,800	0	0	0	0
WTWs2-Resource2	existing	1,036,800	0	0	0	0
WTWs3-Resource3	new	207,360	0	0.31	0	0
WTWs4-Resource4	new	691,200	0	0.26	0	0
WTWs5-Resource1	new	691,200	0	0	0	0
WTWs5-Resource3	new	691200	0	0.31	0	0

2.1.3 Oslo UWS representation in the WaterMet^2 model

Oslo UWS model is currently represented as a single WaterMet^{2}subcatchment. This is because there is not much data currently available in terms of interconnections of main pipelines, service reservoirs and WTWs. Furthermore, in order to create more than one subcatchment, the least essential data would be the details of how the main pipelines are connected with each other and with service reservoirs, WTWs and water resources. Due to the same reason, only one local area is defined inside the subcatchment. In other words, the Oslo water demand will be defined in one local area. The specification of the local area in the Oslo WaterMet^2 model for the first year of analysis (i.e. 2011) is given in Table 4. Five types of water demand including domestic, industrial, irrigation, frost tapping and unregistered public use are defined and the required data are collected from the available sources of Oslo UWS (Oslo Water 2011a and b). Given the average occupancy of each domestic property in Oslo equal to 3, the number of properties would be equal to 202,419 with respect to the population of 607,257 in 2011 for Oslo city.

Table 4: Local areas in the Oslo WaterMet^{2}model

Name of local area	*Indoor water demand (L/day per capita)*	*Industrial/ commercial demand (m^3/day)*	*Irrigation demand (m^3/day)*	*Frost tapping (m^3/day)*	*Unregistered public use (L/day per capita)*	*Occupancy*
1	160	54,795	63,783	35,000	15	3

The daily variations of water demand for domestic, garden watering (plant irrigation) and frost tapping in Oslo over any year are assumed to be calculated as:

$$DV = \frac{T_i}{T_{ave}} \tag{1}$$

$$T_{ave} = \frac{\sum_{i=1}^{n} T_i}{n} \tag{2}$$

where DV = daily variation of the water demand; T_i =average temperature of i th day of the year; T_{ave} =average temperature during the days of the year on which the water demand is used; n = total number of the days of the year which the water demand is used. Note that n is different for various water demands in Oslo. This value for plant irrigation for gardens and public open spaces in Oslo is equal to 108 which is the time interval from 15 May to 31 August. However, this value for frost tapping in Oslo is equal to 151 which is the freezing time between 1 November and 31 March in Oslo (Oslo Water 2011b). Hence, the coefficients of daily variations for water demand can be calculated during the year (Fig 5). These coefficients will be applied for all years of the planning horizon. The daily variation of industrial water demand is assumed to be constant during the year.

Moreover, the annual increase of water demand for domestic, industrial and plant irrigation in Oslo is assumed based on the fast growth of population over the planning horizon (Oslo Water 2011b) which is shown in Fig. 6 and Table 5. It is assumed that frost tapping does not change over the planning horizon. Therefore, the actual water demand for each day over the planning horizon is calculated as

$$AD_{ijk} = D_i \times Cd_{ij} \times \sum_{m=1}^{k} Ca_{im} \tag{3}$$

where AD_{ijk} =actual water demand for category i and j th day of year and k th year over the planning horizon; D_i =average water demand for category i (Table 4); Cd_{ij} =coefficient of daily variation for category i and j th day of year (Fig. 5) ; and Ca_{im} =coefficient of annual increase for category i and m thy ear over the planning horizon (Table 5).

Table 5: Common ratio of annual variations for different categories of water demands in Oslo between 2010 and 2040

	Water Demand	*2010-2030*	*2030-2040*
1	Domestic	1.02	1.01
2	Industry	1.02	1.01
3	Plant irrigation	1.02	1.01
4	Frost tapping	1	1
5	Unregistered public use	1.02	1.01

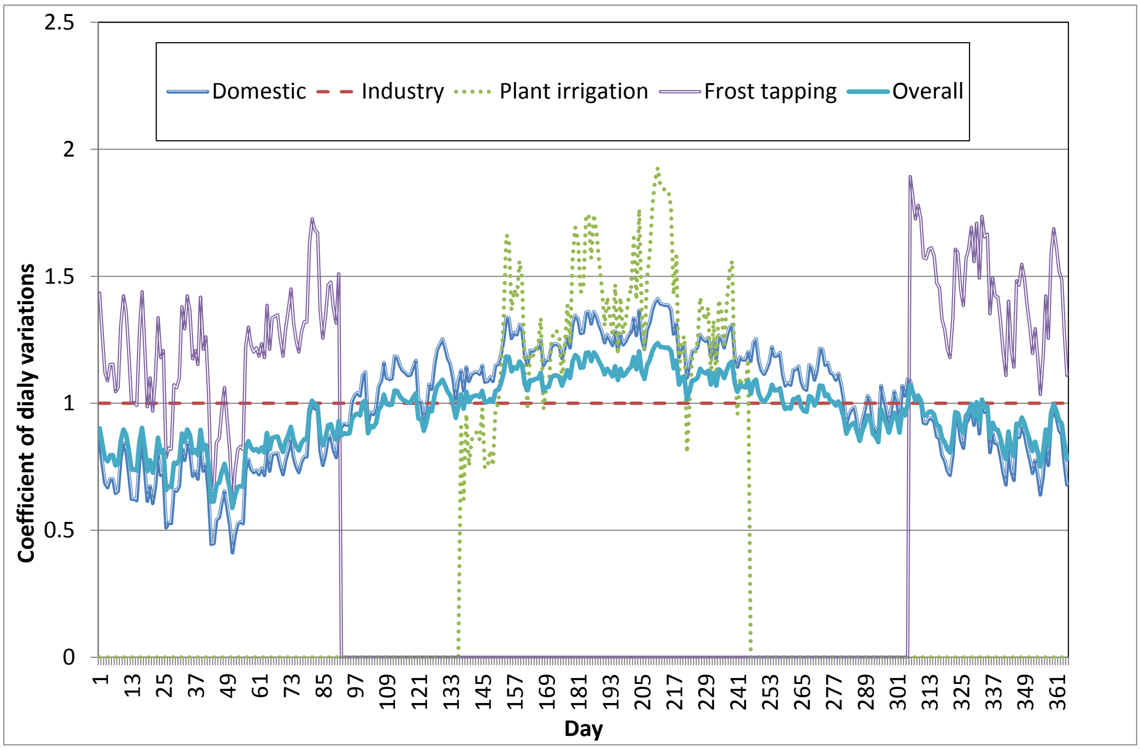

Figure 5: Coefficients of daily variations for different categories of water demand in Oslo

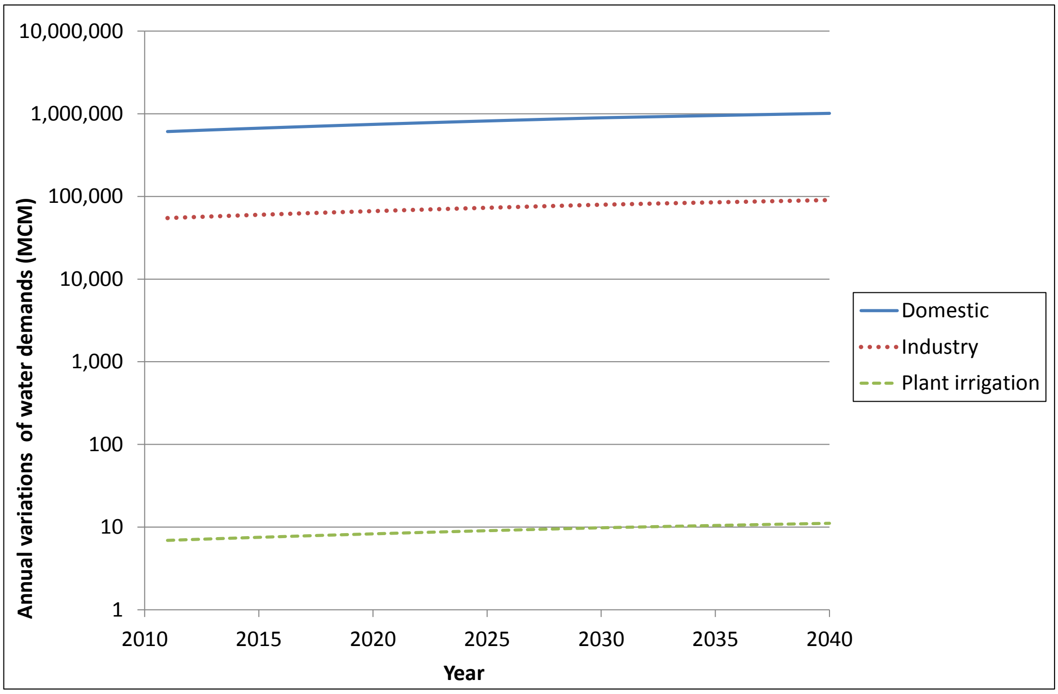

Figure 6: Annual variation in different types of water demand in Oslo between 2010-2040

2.1.4 Pipelines

It is assumed that the single defined WaterMet² subcatchment contains the whole database of the Oslo pipelines. This database comprising 28,442 pipes with lengths greater than 10 metres lists many pipe-characteristics (i.e. material type, length, diameter and age of pipes) in the UWS. A summary of this database is given in Table 6 and represented in Fig. 7.

Table 6: A summary of pipelines characteristics in Oslo UWS

Material type	*Total numbers*	*Total lengths (km)*	*Diameter range (mm)*	*Weighted average diameter (mm)*	*Age range (year)*	*Weighted average age (year)*
Concrete	3	0.09	150	150	37	37
Ductile iron	11,680	462.1	50-1200	249	0-126	30
GRP	11	0.7	40-600	474	16-70	40
Grey cast iron	15,735	776.7	40-900	193	3-152	75
Mild steel	593	45.1	125-1600	582	15-141	61
PE	203	17.3	32-700	220	0-107	19
PVC	217	8.4	50-600	165	0-52	22
Total	**28,442**	**1,310,450**	**32-1600**	**226**	**0-152**	**58**

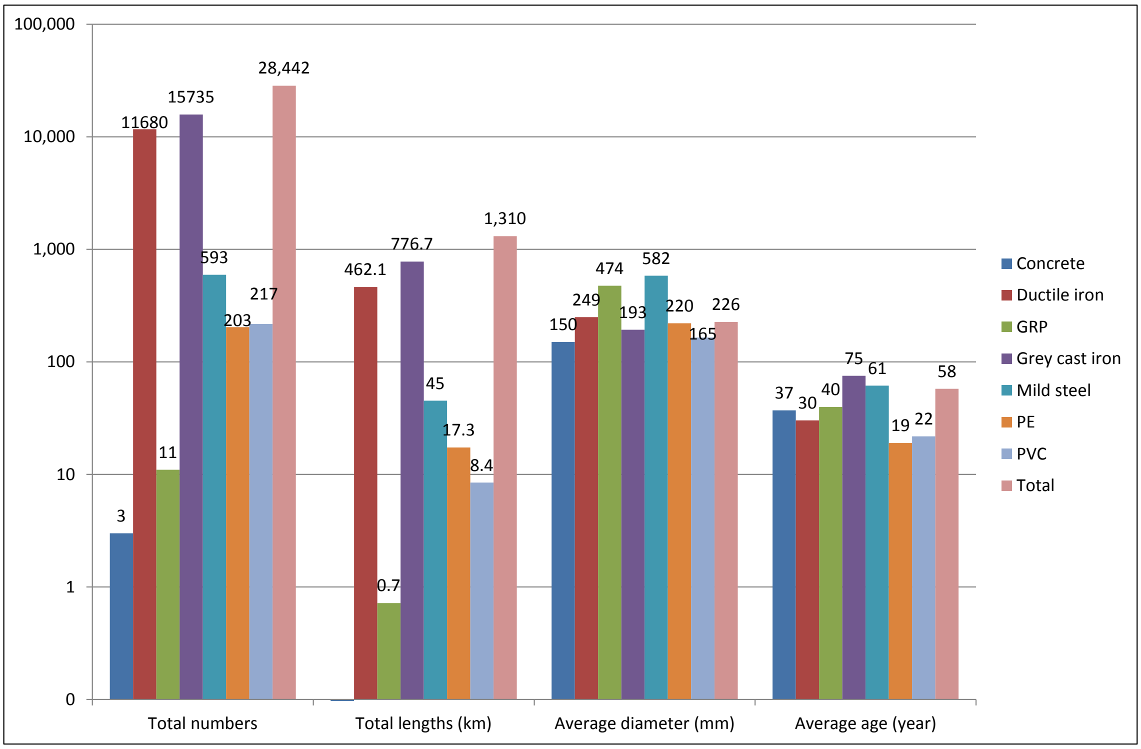

Figure 7: Summary of pipeline characteristics in Oslo UWS

For the existing Oslo UWS, pipelines connecting subcatchments to WTWs are divided into two parts whose specifications which will be used by the WaterMet² model are given in Table 7. In the state of supplying water only from existing water resources, it is assumed that 90% of water demand is supplied from WTWs#1 (Oset) and the remaining 10% is supplied from WTWs#2 (Skullerud). Similarly, the total operational cost of Oslo WTWs obtained from input data is split up into 90% and 10% for the two WTWs, respectively. It is also assumed that the total leakage percentage (22%) is only allocated to pipelines.

Table 7: Specification of pipelines modelled in WaterMet²

Name of pipeline	*Capacity (m3/day)*	*Leakage (%)*	*Annual rehabilitation (%)*	*Electricity (kWh/m³)*	*Fossil fuel (kg/m³)*	*Operational cost (Euro/year)*
Subcatchment1-WTW1	370,000	22	1	0.44	0.00045	25,830,000
Subcatchment1-WTW2	43,200	22	1	0.44	0.00045	2,870,000

Figure 8: Layout of existing Oslo water supply system

2.2 Intervention strategies

The alternative UWS intervention strategies can be thought of as combinations of individual options assessed against the planning horizon. These individual options are introduced below.

1) **New water resources**

Four selected alternatives in the analysis of new raw water resources for Oslo UWS will be used in this report as intervention options (Oslo Water, 2011a) which are shown in Figs. 9-12:

a) New raw water resource at Holsfjorden Lake and two new WTWs (#3 and #5) described in option 'A2' in the relevant report shown in Fig. 9. This option is assumed to be in operation in 2020.

Figure 9: Layout of Oslo water supply system for intervention option A2

b) New raw water resource at Holsfjorden Lake and the two WTWs (#3 and #5) described in option 'A3' in the relevant report shown in Fig. 10. This option is assumed to be in operation in 2020.

Figure 10: Layout of Oslo water supply system for intervention option A3

c) New raw water resource at Glomma River and the two WTWs (#4 and #5) described in option 'B2' in the relevant report shown in Fig. 11. This option is assumed to be in operation in 2020.

Figure 11: Layout of Oslo water supply system for intervention option B2

d) New raw water resource at Holsfjorden Lake and the two WTWs (#3 and #5) described in option 'C1' in the relevant report shown in Fig. 12. This option is assumed to be in operation in 2020.

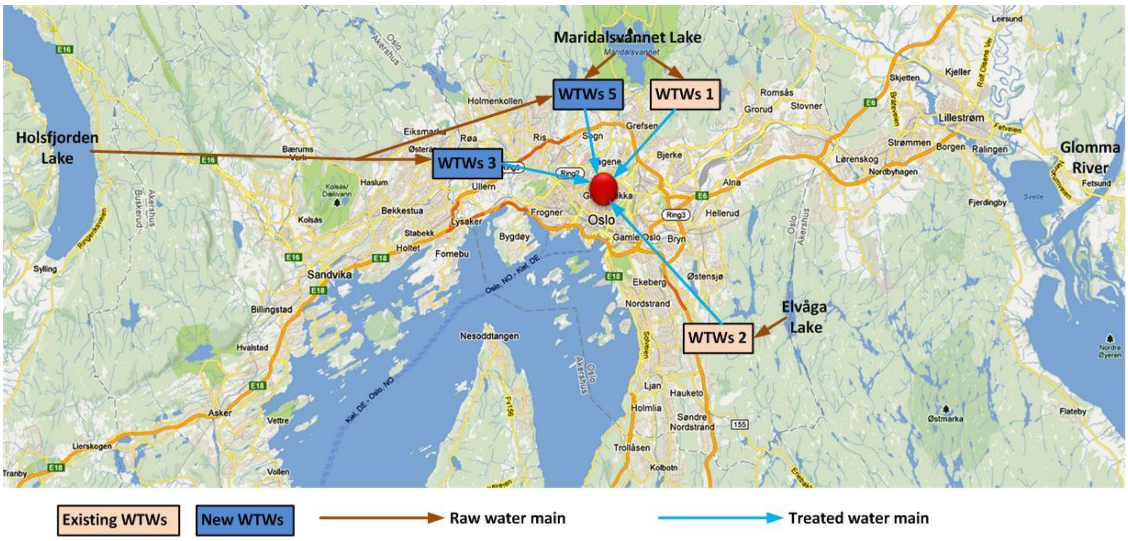

Figure 12: Layout of Oslo water supply system for intervention option C1

In the WaterMet[2] model, the percentage split of water demand of the WaterMet[2] subcatchment from each upstream WTWs needs to be specified. As mentioned earlier in this report, the percentage split of the current water demand from the two upstream WTWs is 0.90 and 0.10 for Oset and Skullerud WTWs, respectively (see Fig. 8). Once new water resources and WTWs are built, the percentage split of water demand for the WaterMet² subcatchment from each upstream WTWs is updated according to the capacity of trunk mains connecting water sources to WTWs (Oslo Water, 2011a). These percentage split is given in Table 3. Table 8 gives these percentage splits each of which should be seen according to one of the Figs. 8-12.

Table 8: Percentage split of flow of the WaterMet² subcatchment from upstream WTWs for each intervention option

Name of WTWs	*WTWs ID*	*Current water resources*	*A2/A3*	*B2*	*C1*
Oset	1	0.90	0.38	0.38	0.38
Skullerud	2	0.10	0.05	0.05	0.05
Holsfjorden Lake	3	0	0.20	0	0.20
Glomma river	4	0	0	0.20	0
New Oset	5	0	0.37	0.37	0.37

2) **Water demand management (by installing additional water meters):** It is assumed that water metering coverage of customers will increase annually by installing a specified number of additional water meters (constant percentage of total) for domestic customers in households where water is not metered. The specified number of additional water meters for each year is represented in the WaterMet² model by the following constant percentages of total properties:

   a) 1% additional annual water meter installation

   b) 3% additional annual water meter installation

   c) 5% additional annual water meter installation

   d) 10% additional annual water meter installation

   In addition, the following key assumptions are taken into account for this type of intervention option:

   a) The installation of new water meters will start from 2015

   b) As the percentage of water meters currently installed for domestic customers in Oslo city is negligible, it is assumed that no water meters are installed for domestic customers at the beginning of planning horizon (Comox valley record 2011).

   c) The annual cost of installing new water meters is evenly distributed throughout the year.

   d) Once a new water meter is installed for a customer, the water demand per capita of that customer will decrease by a constant rate of 10% from that point in time (Oslo Water, 2011b).

e) The installation cost for each water meter is assumed to be 303 Euros including 94 Euros for survey and 209 Euros for installation within the property (Southern water 2011). The data used are from the UK because no such data were provided by Oslo VAV.

3) **Increase rate of pipeline rehabilitation:** It is assumed that the current annual rate of pipeline rehabilitation (e.g. equal to 1% in the Oslo case study) will increase by the following constant percentage of total pipeline length.

   a) 0.2% additional annual rehabilitation

   b) 0.5% additional annual rehabilitation

   c) 1.0% additional annual rehabilitation

Oslo VAV has assumed that with the current level of annual rate of pipeline rehabilitation, the leakage percentage would remain constant and no leakage reduction would take place in the Oslo UWS. The leakage percentage in pipelines decreases only after additional annual rehabilitation is taken into consideration. The methodology used in the WaterMet^2 model to calculate leakage reduction associated with the additional annual rehabilitation is based on the one proposed by Venkatesh G. (2012), which is briefly described here. The principal assumptions for this type of intervention and the methodology in the WaterMet^2 model are:

- Annual rehabilitation is represented as percentage of the total length of pipes in the UWS. It implies the portion of the total pipelines which will be rehabilitated annually.
- Additional annual rehabilitation as an intervention option in Oslo UWS will be taken into consideration from 2015.
- The existing pipes in the system (i.e. the ones that are not subject to rehabilitation) are assumed to have a constant predefined percentage of leakage over the planning horizon. This is due to the fact that Oslo VAV assumes that the total leakage amount would be constant as long as the current level of rehabilitation is preserved.
- The existing leakage is allocated to all current pipes (see below). Once a pipe is rehabilitated, the respective leakage will be subtracted from the total leakage amount (i.e. it is assumed that rehabilitated pipes have zero leakage).
- Once rehabilitation is carried out each year, the cost of rehabilitation including labour, diesel and material costs as well as the associated GHG emissions are calculated based on total cost for the materials and diesel fuel consumed for rehabilitation given in appendices B and C (Ugarelli et al. 2008). This calculated cost is then evenly distributed over the year.

The following two-step procedure is used for calculating system-level leakage reduction:

- The contribution to the leakage percentage and the amount of leakage for each pipe are calculated beforehand:

$$CP_i = \frac{A_i \times L_i}{\sum_{n=1}^{m} A_n \times L_n} \tag{4}$$

$$Leak_i = CP_i \times a \tag{5}$$

where CP_i=coefficient of contribution to leakage percentage for pipe i, A_i =Age of pipe i (year); L_i= length of pipe i (m); m=the number of pipes; $Leak_i$=leakage amount in pipe i and a=leakage percentage. Total leakage can also be calculated as the sum of the leakage in all pipes. Here it is assumed that each pipe contributes to the total leakage amount proportional to its age and length as a linear relationship (Venkatesh 2012).

- If extra annual rehabilitation is applied in a year, the 'oldest-first' rehabilitation approach is used to calculate the leakage reduction during that year. This means that the oldest pipes with total lengths less than or equal to the total length of annual rehabilitated pipes are rehabilitated in the relevant year. Accordingly, the contribution to leakage percentage (CP_i) related to these pipes is assumed to be zero, and consequently, the leakage amount of these pipes ($Leak_i$) will be zero and the total amount of the leakage will decrease.

The age of rehabilitated pipes is set equal to zero at the time of rehabilitation, while the ages of the other pipes in the network are increased by one year. This enables the WaterMet^2 model to calculate the average age of pipes in the UWS during each year as:

$$A_{av} = \frac{\sum_{n=1}^{m} A_n \times L_n}{\sum_{n=1}^{m} L_n} \tag{6}$$

where A_{av}=Average age of pipes in the UWS (years), A_n =Age of pipe n (years); L_n= Length of pipe n (metres) and m=the number of pipes.

For example, given that the current level of annual rehabilitation and percentage of leakage in the Oslo UWS are 1% and 22% respectively, a leakage volume equivalent to 22% of total water demand is expected from the Oslo UWS. If additional annual rehabilitation of 0.5% is planned to start from a year in the planning horizon, the leakage calculations are as follows:

- The total percentage of annual rehabilitation would be 1.5%. Hence, given the total length of pipeline in Oslo to be 1,310,450 metres (Table 7), the total length of pipes rehabilitated in each year would be 19,657 metres
- The oldest pipes with total length less than or equal to the total length of annual rehabilitation (i.e. 19,657 metres) are rehabilitated in each year sequentially. This means that during each year, the total leakage volume associated with the rehabilitated pipes according to Eqs. (4) and (5) during that year will be subtracted from the total volume of leakage of the previous year.

Based on the individual intervention options referred to above, 28 intervention strategies composed of either a single strategy option (simple strategy) or two strategy options (complex strategy) are introduced in Table 9 for analysis by the WaterMet^2 model in Oslo case study.

Table 9: Intervention strategies in the WaterMet^2 model

Intervention Strategy				
Intervention Strategy	*Intervention Options*			
	Intervention Option#1		*Intervention Option#2*	
ID	*Description*	*Timing*	*Description*	*Timing*
1	business as usual	-	-	-
2	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A2	2020	-	-
3	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A3	2020	-	-
4	Addition of new raw water resource at Glomma River and two WTWs described in B2	2020	-	-
5	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in C1	2020	-	-
6	1% additional annual water meter installation	every year from 2015	-	-
7	3% additional annual water meter installation	every year from 2015	-	-
8	5% additional annual water meter installation	every year from 2015	-	-

Intervention Strategy				
Intervention Strategy	*Intervention Options*			
	Intervention Option#1		*Intervention Option#2*	
ID	*Description*	*Timing*	*Description*	*Timing*
9	10% additional annual water meter installation	every year from 2015	-	-
10	0.2% additional annual rehabilitation	every year from 2015	-	-
11	0.5% additional annual rehabilitation	every year from 2015	-	-
12	1% additional annual rehabilitation	every year from 2015	-	-
13	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A2	2020	0.5% additional annual rehabilitation	every year from 2015
14	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A3	2020	0.5% additional annual rehabilitation	every year from 2015
15	Addition of new raw water resource at Glomma River and two WTWs described in B2	2020	0.5% additional annual rehabilitation	every year from 2015
16	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in C1	2020	0.5% additional annual rehabilitation	every year from 2015
17	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A2	2020	0.2% additional annual rehabilitation	every year from 2015

Intervention Strategy				
Intervention Strategy	*Intervention Options*			
	Intervention Option#1		*Intervention Option#2*	
ID	*Description*	*Timing*	*Description*	*Timing*
18	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A3	2020	0.2% additional annual rehabilitation	every year from 2015
19	Addition of new raw water resource at Glomma River and two WTWs described in B2	2020	0.2% additional annual rehabilitation	every year from 2015
20	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in C1	2020	0.2% additional annual rehabilitation	every year from 2015
21	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A2	2020	10% additional annual water meter installation	every year from 2015
22	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in A3	2020	10% additional annual water meter installation	every year from 2015
23	Addition of new raw water resource at Glomma River and two WTWs described in B2	2020	10% additional annual water meter installation	every year from 2015
24	Addition of new raw water resource at Holsfjorden Lake and two WTWs described in C1	2020	10% additional annual water meter installation	every year from 2015
25	0.5% additional annual rehabilitation	every year from 2015	5% additional annual water meter installation	every year from 2015
26	0.5% additional annual rehabilitation	every year from 2015	10% additional annual water meter installation	every year from 2015

Intervention Strategy				
Intervention Strategy	*Intervention Options*			
	Intervention Option#1		*Intervention Option#2*	
ID	*Description*	*Timing*	*Description*	*Timing*
27	0.2% additional annual rehabilitation	every year from 2015	5% additional annual water meter installation	every year from 2015
28	0.2% additional annual rehabilitation	every year from 2015	10% additional annual water meter installation	every year from 2015

2.3 Evaluation Criteria

Different intervention strategies introduced previously need to be evaluated by using some criteria in order to rank these strategies. The criteria selected should cover the different dimensions of sustainability in the UWS by taking into account social, environmental and economic aspects. In this analysis, eight criteria including five quantitative and three qualitative criteria are introduced to quantify the key performances indicators in the UWS. The five quantitative criteria will be quantified by the WaterMet^2 model while three qualitative criteria will be quantified by experts' opinions and judgements.

2.3.1 Quantitative criteria

Quantitative criteria in Oslo UWS should cover all categories of a system analysis. Therefore, they are extracted from economy, risk-related, technical and environmental issues. These criteria and the method which will be employed by the WaterMet^2 model for their calculations are discussed in the following sub-sections:

1. Discounted capital costs: They include the total investments made in Oslo UWS discounted in year 2011 associated with:

- ✓ building new water resources and WTWs;
- ✓ installation of additional water meters;
- ✓ annual rehabilitation only when additional rehabilitation is applied.

It is assumed that the expenditure on building new water resources will be spent in the year in which the new water resources are first brought on-stream. Also, the expenditures relating to water meters installation and rehabilitation will be distributed uniformly over the year in which these costs are incurred.

2. Discounted O&M costs: it covers both fixed and variable (water consumption-dependant) costs. The first category is related to all fixed costs such as labour and maintenance costs in different components of the UWS such as water resources, WTWs and service reservoirs. This cost for each component of UWS is represented as an annual constant rate in the WaterMet^2 model. The second category relates to all O&M costs dependent on water consumption in the UWS such as those spent on chemicals and energy. Note that the total O&M costs over the planning horizon are finally discounted in year 2011 in order to represent this criterion. The annual discount rate is also assumed to be 3% although other rates can be examined through sensitivity analysis.

3. Reliability of water supply: This is calculated based on the ratio between the total water delivered to customers and the total water demand over the planning horizon:

$$\mathrm{Re}\,liability = \frac{\sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} D_i} \quad (7)$$

where D_i and S_i = water demand and water delivered at ith time step, respectively and n=number of time steps over the planning horizon.

4. Total water leakage: This is calculated based on the summation of the time series of leakage volume in the water distribution systems with respect to the degree of pipeline rehabilitation during the planning horizon as described in the previous sections.

5. Total GHG emissions: The total amount of energy in the form of either fossil fuel or electricity as well as embodied (indirect) energy in additional pipeline rehabilitation, and chemicals used for the treatment of the raw water is calculated over the planning horizon. Then the total GHG emissions will be calculated in kg-CO_2 equivalents. The assumed values of GHG emissions as a result of energy consumption in Oslo as well as embodied energy and associated GHG emissions resulting from chemicals and materials consumption in pipeline rehabilitation are given in Appendices A and B.

2.3.2 Qualitative criteria

The qualitative criteria in the UWS are those subjective sustainability issues which can only be quantified based on the experts' opinions and judgements. In this analysis, intervention strategies are ranked against each of the three qualitative criteria using five linguistic terms (extremely low, low, medium, high and extremely high) to represent different qualitative categories of subjective judgments. Instead of qualitative categories (linguistic terms), they are ranked on a scale of 1 to 10 as 1-2, 3-4, 5-6, 7-8 and 9-10, representing extremely low, low, medium, high and extremely high, respectively.

6. **Health risks:** The potential health risks particularly associated with source water quality related in different strategies.

7. **Social acceptance:** It is related to social acceptance of intervention strategies, for instance, the acceptance of the society of installing water meters, or otherwise.

8. Company acceptance: it is related to acceptance of companies - either private or public – of the intervention strategy. For instance, how much the companies will support the options related to adding new water resources compared to those associated with water meter installation or additional annual rehabilitation.

2.4 Analysis Scenario

Although a variety of different states can be envisaged for population growth and water resource availability in Oslo UWS, this analysis takes into consideration at present only the single scenario with following characteristics:

- **Increase in water demand due to population growth:** The highest rate of water demand will be considered by assuming the fast population growth projection over the planning horizon as described in section 2.1.3.
- **Normal water availability in the existing raw water resources:** The time-series of water inflow at the two existing raw water resource is assumed to be normal combining dry and wet years during the planning horizon as described in section 2.1.1.

3 Results and Discussion

The WaterMet^2 Oslo model was first created for the 'business as usual' (BAU) strategy in which no intervention is employed throughout the planning horizon. Obviously, the evaluation criteria for the 'do-nothing' strategy are the benchmark and any improvements subject to any intervention strategies are compared to this strategy. For a better assessment of the introduced intervention strategies, the results are analysed in three parts. In the first part, simple and complex intervention strategies comprising either one or two individual intervention options respectively, are compared with each other, and with the BAU strategy. In the second part, all intervention strategies quantified by the WaterMet^2 model are ranked based on the compromise programming MCDA[1]method (Andre and Romero 2008; Yu 1985). Finally, based on this approach, a number of superior intervention strategies will be selected and analysed in more detail.

3.1 Simple and complex intervention strategies

Simple intervention strategies are those which only contain one type of intervention option throughout the planning horizon. Three individual intervention options including adding new water resource, additional annual water meter installation and additional annual rehabilitation introduce three types of simple intervention strategies. Each of these simple strategies is further split up into various levels of interventions to find out which levels are more appropriate for the rest of the analysis.

Intervention strategies #2-#5 (Table 10) introduce four different options of adding new water resources in year 2020 in Oslo UWS. The quantified evaluation criteria related to these strategies and the BAU strategy are given in Table 10 and shown in Fig. 13. As it can be seen from Table 10, the water

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[1] Multi-criteria decision analysis

supply reliability increased from 95.4% in the BAU strategy to almost 100% in strategies with additional water sources in the UWS. This is because the BAU strategy will suffer from water shortage in the future due to the increase in water demand and limited water available at the sources. However by adding new, virtually unlimited capacity of water source, this issue is resolved in other strategies. However, increased reliability of supply is achieved at the cost of large capital investment required for building new water resources and associated WTWs (Fig. 13). The average annual GHG emissions and O&M costs increase too (10% and 50%, respectively) with the installation of new sources and WTWs when compared to the BAU strategy. The average annual leakage has slightly increased for new water resources. This is because water demand is supplied more in the strategies with additional water sources than the BAU strategies over the planning horizon and hence the leakage as a percentage of water demand would increase.

Table 10: Result of applying simple interventions related to new water resources in the UWS

Strategy number (name)	Capital cost [MEuros]	O&M Cost [MEuros/ year]	Reliability of supply [%]	Leakage [MCM/ year]	GHG emissions [10^3Tons/ year]
#1 (business as usual)	0.00	230.93	95.43	20.34	655.92
#2 (Only A2)	389.16	269.60	99.94	21.30	724.94
#3 (Only A3)	479.94	269.60	99.94	21.30	724.94
#4 (Only B2)	540.21	269.56	99.94	21.30	724.46
#5 (Only C1)	326.66	269.60	99.94	21.30	724.94

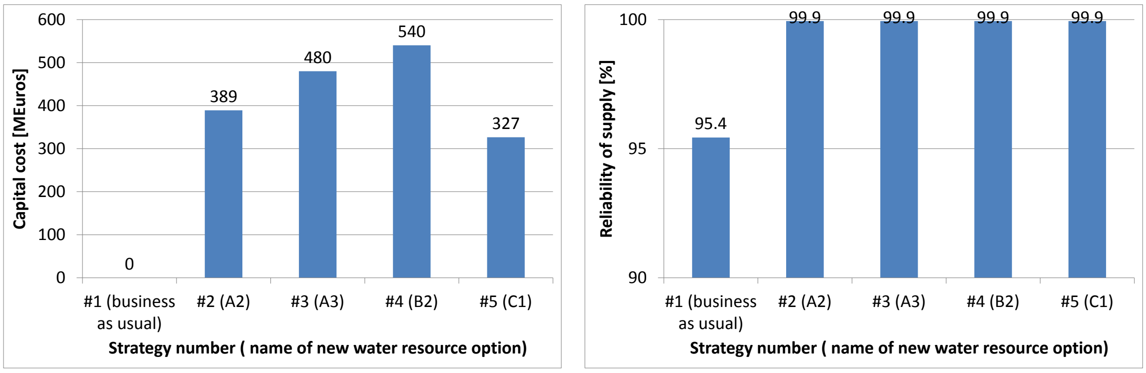


Figure 13: Comparison of two quantitative evaluation criteria amongst simple strategies (adding new water resources) and the BAU strategy

In contrast to the enhancement of water supply, the second set of the intervention strategies strive to improve demand management by installing water meters which, in turn, reduced the amount of water used per capita. Here, intervention strategies #6-#9 (Table 11) examine different levels of additional annual water meter installation. Fig. 14 draws a comparison of two evaluation criteria between the BAU strategy and these strategies, with associated results (Results in Table 11). As it can be seen, by introducing a higher level of water metering, water supply reliability will gradually increase and average annual GHG emissions, leakage and O&M costs will gradually decrease, all because of the reduction in water consumption per capita (which is a consequence of additional water metering). However, the associated capital cost will steadily increase due to annual investment required for water meter installation. Unlike the strategies related to increasing water supply (Strategies #2-#5), strategies related to water demand management would lead to decrease in leakage due to consumption reduction. GHG emissions, when water supply increases, rises by 10%. .However, with effective water demand management, this rate can be brought down to around 2.2%.

Table 11: Result of applying different levels of simple strategy related to annual water meter installation in the UWS

Intervention Strategy number (name)	*Capital cost [MEuros]*	*O&M Cost [MEuros/ year]*	*Reliability of supply [%]*	*Leakage [MCM/ year]*	*GHG emissions [10^3Tons/ year]*
#1 (business as usual)	0.00	230.93	95.43	20.34	655.92
#6 (1% annual water meter installation)	9.21	230.60	95.52	20.30	654.61
#7 (3% annual water meter installation)	27.63	229.95	95.71	20.22	652.00
#8 (5% annual water meter installation)	39.35	228.99	96.08	20.09	647.91
#9 (10% additional water meter installation)	45.13	227.18	96.55	19.89	641.26

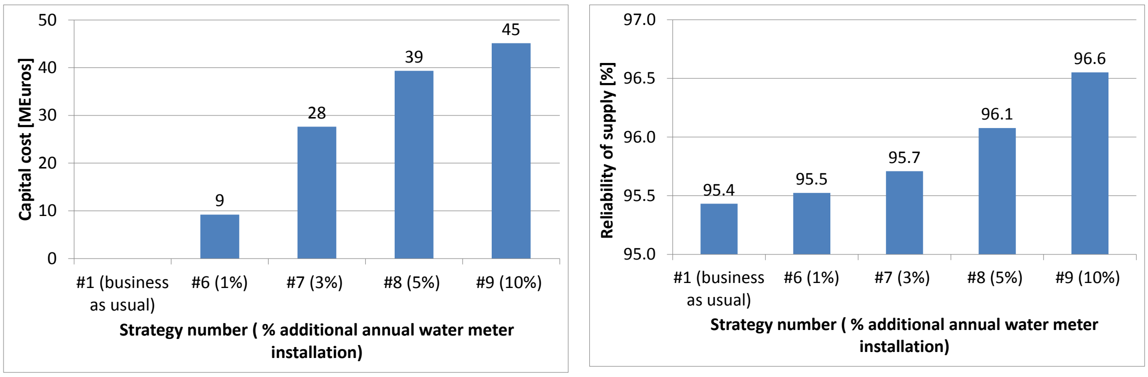


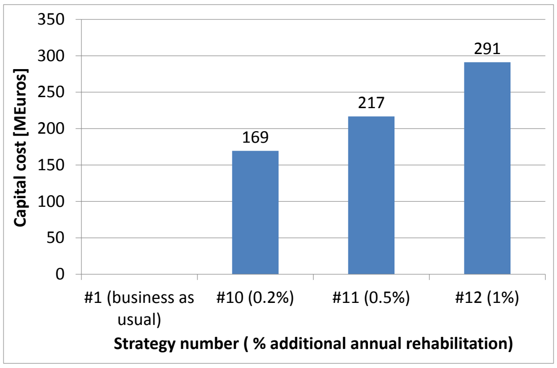
Figure 14: Comparison of two evaluation criteria amongst simple strategies (additional annual water meter installation) and the BAU strategy

In addition to applying water demand management strategies targeted at the consumer, in the UWS, demand can be reduced by controlling the leakage rate. Whereas the strategies#6 - #9 reduce water demand by reducing water demand consumption, the strategies #10 - #12 examines water demand reduction by decrease in the amount of leakage in the UWS. Thus, three levels of additional annual rehabilitation introduced in strategies#10- #12 are compared here with those of the BAU approach (Fig. 15 and Table 12). Contrary to the negligible improvement in water supply reliability (up to 1.35%) when applying the highest rate of water meter installation (10%), the reliability would improve rapidly when performing rehabilitation and reach 98.1% - a 2.8% improvement. Further, the strategies containing pipeline rehabilitation are prone to extensively reduce annual average leakage up to approximately 45% while the maximum reduction in the same criterion for strategies with water meter installation is only 2%. Despite improvement in these two criteria in rehabilitation strategies, they are not as good as water meter installation strategies with respect to the GHG emissions and capital costs. For example, although more GHG emission reductions may be expected for rehabilitation strategies due to the huge reduction in water and its treatment, the total GHG emissions in rehabilitation strategies increase owing to a higher rate of embodied GHG emissions from the materials used for rehabilitation. In addition, the total capital costs for rehabilitation strategies are over thrice as large as those for water meter installation. The improvement in the annual O&M costs in both sets of strategies is very negligible and also quite similar. Although leakage amount decrease sharply, annual O&M cost decrease slightly due to less water leaked through the UWS and hence the energy required for transmission and treatment is avoided. This may be justified due to lesser effect of annual variable O&M cost on the total O&M costs compared with fixed ones in the UWS.

Here, the comparison of all 28 intervention strategies comprising either one intervention option (simple strategies #2 - #12) or two intervention options (complex strategies #13 - #28) are compared with the BAU strategy (#1) with respect to the quantified evaluation criteria which are given in Table 13. These evaluation criteria were quantified by the WaterMet^2 model over the planning horizon.

Table 12: Results of applying different levels of simple intervention strategy related to additional annual rehabilitation in the UWS

Intervention Strategy number (name)	Capital cost [MEuros]	O&M Cost [MEuros/ year]	Reliability of supply [%]	Leakage [MCM/ year]	GHG emissions [10^3Tons/ year]
#1 (business as usual)	0.00	230.93	95.43	20.34	655.92
#10 (0.2% additional annual rehabilitation)	169.39	223.93	97.29	14.12	630.40
#11 (0.5% additional annual rehabilitation)	216.70	222.87	97.59	13.13	626.45
#12 (1% additional annual rehabilitation)	291.18	221.19	98.02	11.62	620.22



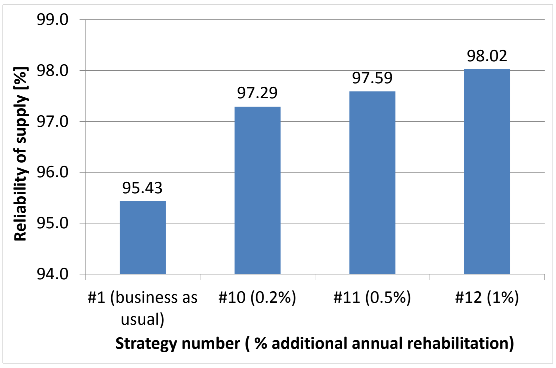


Figure 15: Evaluation criteria related to individual intervention options of additional annual rehabilitation (intervention strategies#10-12) and BAU strategies

The assessment of the strategies altogether may be carried out by focusing on each evaluation criterion separately (Figs 16-20). Fig. 16 shows the total capital cost of all intervention strategies over the planning horizon discounted in year 2011. As it can be seen, when applying an additional water resource as an intervention strategy to boost the supply side in water supply/demand balance, the total capital cost sharply rises compared with other strategies. This is due to high capital investment required for adding a new water resource in the UWS. This considerable discrepancy in total capital cost may be observed in the Figure even when two other intervention options without any new water source are combined to make up a new strategy (i.e. by comparing strategies #25-#28 with strategies #2 - #5 and #13 -#24).

Fig. 17 shows average annual O&M cost discounted in year 2011 for all strategies. Similarly, the O&M cost for the strategies containing new water resources are greatly higher than other strategies due to the addition of constant costs for new WTWs. Consequently, for the complex strategies containing additional new water sources, envisaged reduction in O&M costs are either by water demand reduction (strategies #21 - #24) or water leakage reduction (strategies #13 - #20)is almost ignored by the significant increase in average annual O&M due to adding new WTWs.

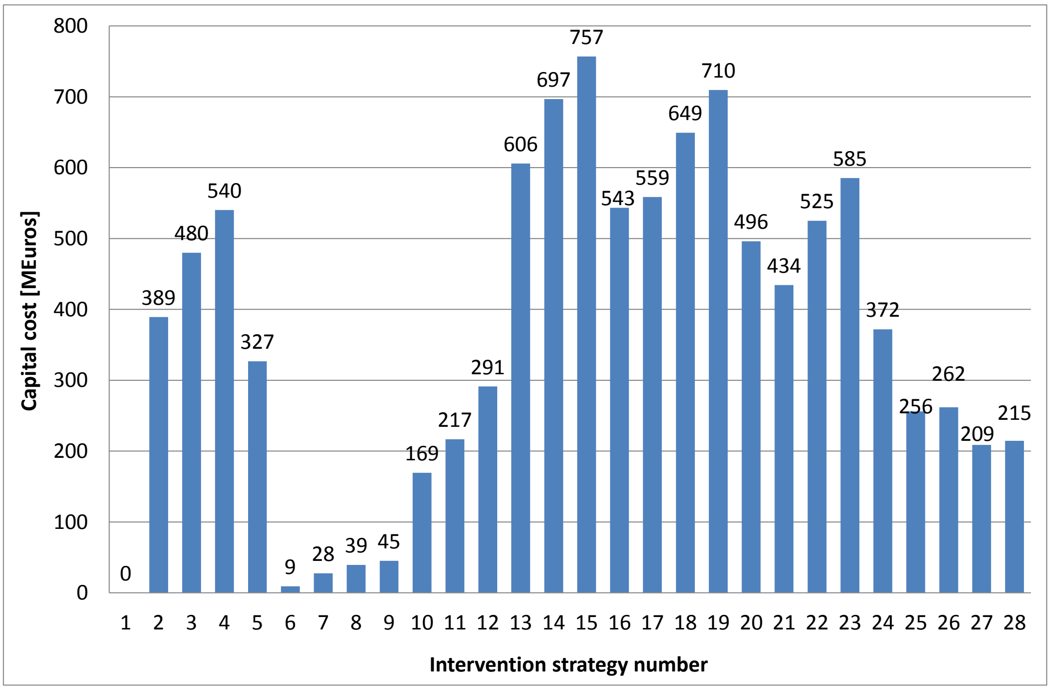


Figure 16: Total capital cost of all intervention strategies over the period 2011-2040 discounted in year 2011

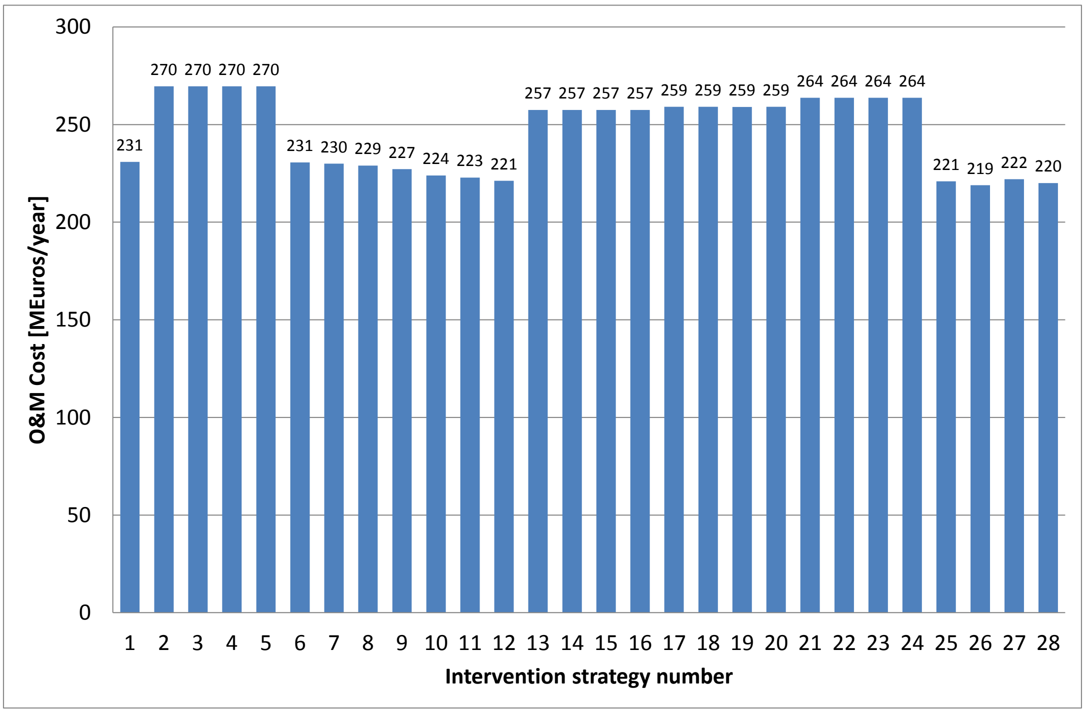


Figure 17: Average annual O&M cost of all intervention strategies over the planning horizon discounted in year 2011

Fig. 18 shows the relevant water supply reliability for all strategies. As expected, the reliability of water supply for the strategies involving the setting-up of new water resources is almost 100 per cent as it can compensate for the water shortage likely to occur over the planning horizon. The next top strategies are those containing both water demand intervention options (#25-#28). Although water demand for these strategies is not fully satisfied (approximately 98 per cent), they can be in compliance with some threshold defined by the UWS authorities. In addition, some noticeable enhancement can be achieved in these strategies vis-à-vis the BAU strategy.

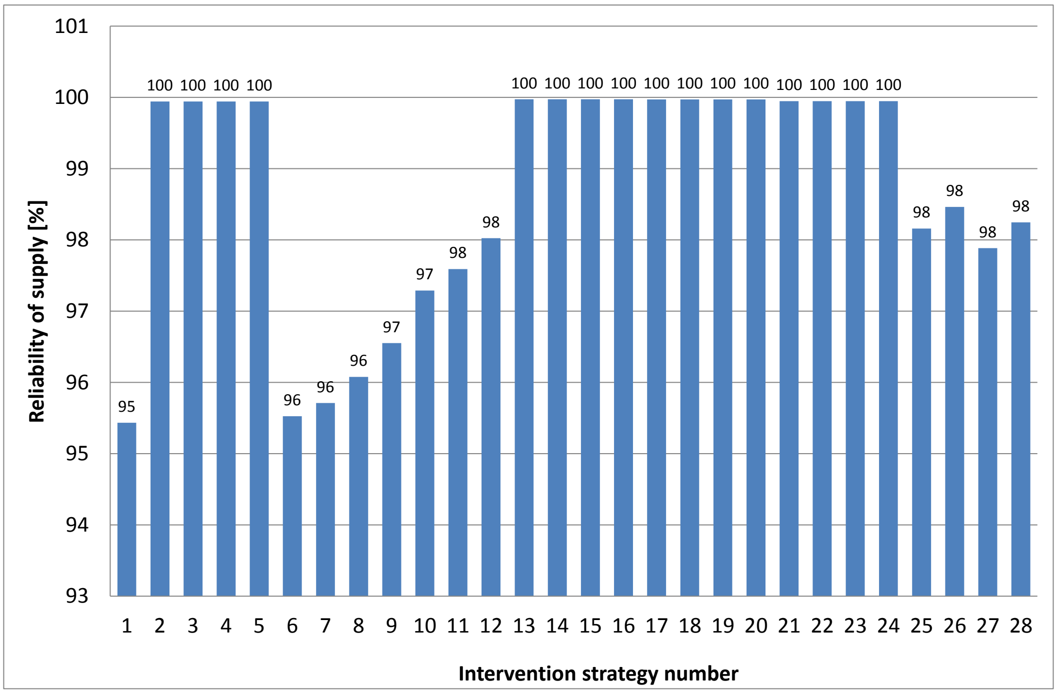


Figure 18: Water supply reliability of Oslo UWS in the period 2011-2040 for all intervention strategies

Fig. 19 represents the respective average annual leakage for all strategies. Needless to say, when any level of additional annual rehabilitation is applied to the UWS, the leakage rate would significantly reduce (strategies #10 - #20 and #24 - #28). For other strategies (strategies #2 - #9 and #21 - #24) not only is no mitigation observed but the annual leakage also increases compared to the BAU strategy. As discussed earlier, this is because water shortage happening during the later parts of the planning horizon is almost resolved in these strategies by adding new water resources and water demand are fully supplied consequently. Hence, more leakage is envisaged as a percentage of total water demand.

Fig. 20 represents the associated average annual GHG emissions for all strategies. The simple strategies comprising only additional new water resources (strategies #2 -#5) will increase the annual GHG emissions by 10%. As previously discussed, this is mainly due to supplying more water demand percentage during the later years of planning horizon. Adding other intervention options to these simple strategies (strategies #13 -#24) will help a little diminish these rates owning to some water-saving techniques and therefore reducing energy demand for treatment in the WTWs. For the strategies employing only water demand reduction (strategies #6 -#12 and #25 -#28), the GHG emissions are almost similar to that in the BAU strategy although, this rate declines for the strategies containing additional annual water meter installation. The is due to the fact that the aforesaid reduction in energy consumption in the UWS is almost offset by the energy consumed for delivering more water during the latter part of the planning horizon as well as embodied energy in pipeline rehabilitation strategies.

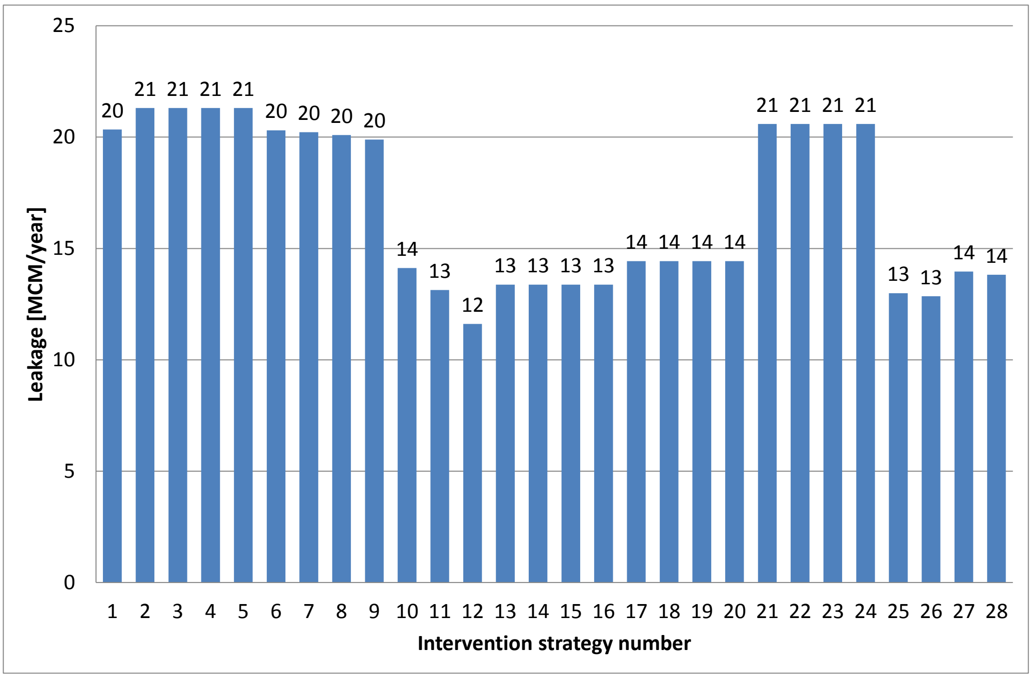


Figure 19: Average annual leakage of Oslo UWS in the period 2011-2040 for all intervention strategies

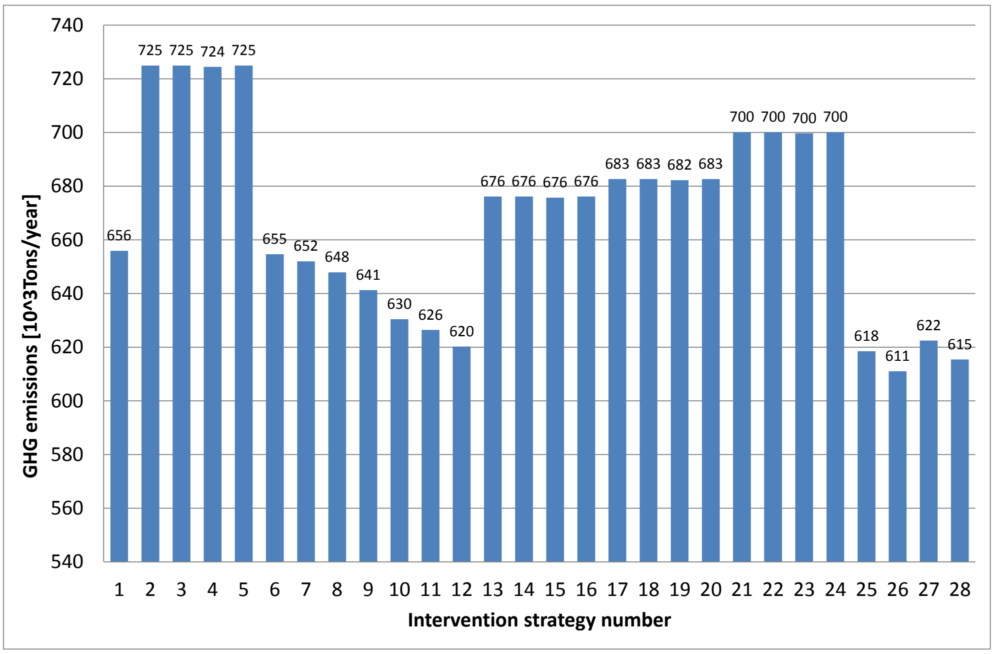


Figure 20: Total GHG emissions of Oslo UWS in the period 2011-2040 for all intervention strategies

3.2 Ranking of strategies with respect to quantitative criteria

To rank different intervention strategies, Compromise Programming (CP) method is used as a MCDA technique. The CP approach calculates a distance function for each strategy based on a subset of efficient solutions (called compromise set) that is nearest with respect to an ideal point, for which all the criteria are optimized (Andre and Romero 2008; Yu 1985). Assuming equal weights for all the criteria, the final ranking of different intervention strategies with respect to all quantitative criteria is given in last column of Table 13. Note that these weighting factors can be changed by the relevant experts in the latter analyses to see the robustness of the result.

Note that the ranking results shown here are for illustration purposes only with the aim to demonstrate what type of analysis can be done and results obtained by using the WaterMet^2 model and the DSS tool that will be developed in WP54. The results shown below cannot be fully trusted at the moment nor should be used to make any real decisions as the current WaterMet^2 model still needs to be further developed, tested and validated. Also, for the time being, the ranking results shown here do not take into account risk-type criteria values that will be calculated using the risk model developed in WP32. The current ranking also does not take into account any specific criteria targets which may render some of the intervention strategies as non-compliant(for example, if target of water supply reliability is e.g. 97%, then a number of intervention strategies shown here would be non-compliant, i.e. should be excluded from ranking). In addition to all this, the intervention strategies analysed are ranked here assuming only one future demand increase scenario. In real life, multiple scenarios of possible future demand, urbanisation, climate change and other changes would need to be considered before a robust solution could be identified.

Based on the ranking results obtained, the following can be inferred: (1) the best rank is for intervention strategy#26 which comprises 0.5% additional annual rehabilitation and 10% additional annual water meter installation. (2) Interestingly, four out of the five top ranks belong to the complex strategies comprising additional annual rehabilitation and additional annual water meter installation (strategies #26, #28, #25 and #27 are ranked first, third, fourth and fifth respectively). The overall benefits of these strategies with respect to all criteria can be summarised as: they are able to considerably reduce the leakage amount, O&M cost and GHG emissions; the reliability of water supply are reasonably satisfied; the capital cost required for implementing these interventions are not as high as other competitive strategies. (3) The BAU strategy is ranked 24th implying that many other more efficient strategies currently employable are able to enhance the UWS performance over the planning horizon.(4) The ranks of the simple intervention strategies containing only additional water resources (20-28) reveal that employing only this type of intervention is inefficient vis-à-vis combining with other intervention options such as strategies#13-16. (5) If one wish to select a simple intervention strategy, additional annual rehabilitation - particularly strategy#12 (ranked 2nd) - may be recommended.

Table 13: Ranking of all intervention strategies with respect to quantitative criteria over the planning horizon

Criteria	*Capital cost*	*O&M Cost*	*Reliability of supply*	*Leakage*	*GHG emissions*	Rank
Units	**MEuros**	**MEuros/year**	**%**	**MCM/year**	**10^3Tons/year**	
Weights	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	
Minimisation	**TRUE**	**TRUE**	**FALSE**	**TRUE**	**TRUE**	
Normalisation minimum	**0.00**	**0.00**	**95.00**	**0.00**	**0.00**	
Normalisation maximum			**100.00**			
Intervention Strategy #1 (business as usual)	0.00	230.93	95.43	20.34	655.92	24
Intervention Strategy #2 (Only A2)	389.16	269.60	99.94	21.30	724.94	23
Intervention Strategy #3 (Only A3)	479.94	269.60	99.94	21.30	724.94	26
Intervention Strategy #4 (Only B2)	540.21	269.56	99.94	21.30	724.46	28
Intervention Strategy #5 (Only C1)	326.66	269.60	99.94	21.30	724.94	21
Intervention Strategy #6 (only 1% additional annual water meter installation)	9.21	230.60	95.52	20.30	654.61	22
Intervention Strategy #7 (only 3% additional annual water meter installation)	27.63	229.95	95.71	20.22	652.00	20
Intervention Strategy #8 (only 5% additional annual water meter installation)	39.35	228.99	96.08	20.09	647.91	15

Criteria	*Capital cost*	*O&M Cost*	*Reliability of supply*	*Leakage*	*GHG emissions*	Rank
Units	**MEuros**	**MEuros/year**	**%**	**MCM/year**	**10^3Tons/year**	
Weights	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	
Minimisation	**TRUE**	**TRUE**	**FALSE**	**TRUE**	**TRUE**	
Normalisation minimum	**0.00**	**0.00**	**95.00**	**0.00**	**0.00**	
Normalisation maximum			**100.00**			
Intervention Strategy #9 (only 10% additional annual water meter installation)	45.13	227.18	96.55	19.89	641.26	12
Intervention Strategy #10 (0.2% additional annual rehabilitation)	169.39	223.93	97.29	14.12	630.40	7
Intervention Strategy #11 (0.5% additional annual rehabilitation)	216.70	222.87	97.59	13.13	626.45	6
Intervention Strategy #12 (1% additional annual rehabilitation)	291.18	221.19	98.02	11.62	620.22	2
Intervention Strategy #13 (A2 & 0.5% additional annual rehabilitation)	605.86	257.50	99.97	13.37	676.15	11
Intervention Strategy #14 (A3 & 0.5% additional annual rehabilitation)	696.64	257.50	99.97	13.37	676.15	14
Intervention Strategy #15 (B2 & 0.5% additional annual rehabilitation)	756.91	257.46	99.97	13.37	675.71	19
Intervention Strategy #16 (C1 & 0.5% additional annual rehabilitation)	543.36	257.50	99.97	13.37	676.15	8
Intervention Strategy #17 (A2 & 0.2% additional annual rehabilitation)	558.55	259.08	99.97	14.43	682.64	10

Criteria	*Capital cost*	*O&M Cost*	*Reliability of supply*	*Leakage*	*GHG emissions*	Rank
Units	**MEuros**	**MEuros/year**	**%**	**MCM/year**	**10^3Tons/year**	
Weights	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	
Minimisation	**TRUE**	**TRUE**	**FALSE**	**TRUE**	**TRUE**	
Normalisation minimum	**0.00**	**0.00**	**95.00**	**0.00**	**0.00**	
Normalisation maximum			**100.00**			
Intervention Strategy #18 (A3 & 0.2% additional annual rehabilitation)	649.33	259.08	99.97	14.43	682.64	13
Intervention Strategy #19 (B2 & 0.2% additional annual rehabilitation)	709.61	259.04	99.97	14.43	682.20	17
Intervention Strategy #20 (C1 & 0.2% additional annual rehabilitation)	496.05	259.08	99.97	14.43	682.64	9
Intervention Strategy #21 (A2 & 10% additional annual water meter installation)	434.29	263.72	99.95	20.59	700.14	18
Intervention Strategy #22 (A3 & 10% additional annual water meter installation)	525.07	263.72	99.95	20.59	700.14	25
Intervention Strategy #23 (B2 & 10% additional annual water meter installation)	585.34	263.68	99.95	20.59	699.68	27
Intervention Strategy #24 (C1 & 10% additional annual water meter installation)	371.78	263.72	99.95	20.59	700.14	16
Intervention Strategy #25 (0.5% additional annual rehabilitation & 5% additional annual water meter installation)	256.05	220.92	98.16	12.99	618.45	4

Criteria	*Capital cost*	*O&M Cost*	*Reliability of supply*	*Leakage*	*GHG emissions*	Rank
Units	**MEuros**	**MEuros/year**	**%**	**MCM/year**	**10^3Tons/year**	
Weights	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	
Minimisation	**TRUE**	**TRUE**	**FALSE**	**TRUE**	**TRUE**	
Normalisation minimum	**0.00**	**0.00**	**95.00**	**0.00**	**0.00**	
Normalisation maximum			**100.00**			
Intervention Strategy #26 (0.5% additional annual rehabilitation & 10% additional annual water meter installation)	261.83	218.92	98.46	12.85	611.03	1
Intervention Strategy #27 (0.2% additional annual rehabilitation & 5% additional annual water meter installation)	208.75	222.00	97.88	13.97	622.48	5
Intervention Strategy #28 (0.2% additional annual rehabilitation & 10% additional annual water meter installation)	214.52	220.07	98.24	13.82	615.39	3

3.3 Assessment of selected intervention strategies

Based on the ranking and the type of interventions employed, six strategies with different combinations of interventions were selected for further analysis as: strategies #1, #2, #9, #12, #13 and #26. These strategies are compared to each other with respect to each quantified criteria, which is shown in Fig. 21. As can be seen, the strategies #2 and #13 containing new water resources have the worst ranks in most criteria, particularly capital cost, O&M cost and GHG emissions although they can provide 100% reliability of water supply. This proves inability of this type of strategies in satisfying the essential performance indicators together. On the other hand, strategies #12 and #26 (the best two ranks in the overall ranking) have almost been amongst the best ranks with respect to different criteria. Fig. 22 represent the direct comparison of the selected intervention strategies with respect to the criteria altogether in one figure. Note that all the criteria were normalised based on the minimization approach. As it can be seen, the strategies #1, #2, #9 and #13 are almost the worst ranks (the maximum values) while the strategies #12 and #26 are often the best ranks (the minimum values).

Moreover, Figs. 23 and 24 indicate the time series of the percentage of water demand delivered and the total leakage for the selected intervention strategies over the period 2011-2040, respectively. For the BAU strategy, the water shortage kicks in shortly after a few years of starting the planning horizon and gradually tends to worsen, particularly in summer (see Fig. 23a). This Figure shows that proceeding with this strategy would even lead to a critically challenging water supply during the last years of planning horizon such that the water demand delivered will reach up to around 70% and even the water shortage will expand during the winter times. This water shortage would also happen for other intervention strategies however it will be completely resolved once new water resources are employed (see Figs. 23b and 238e for strategies #2 and #13 respectively). Strategies #12 and #26 as the two top ranks will improve the minimum water demand delivered to over 80% and 85%, respectively (see Figs. 23d and 23f). These percentages of water supply happening during the last years of planning horizon, although not favourite, can at least postpone that similar water shortage in the BAU strategy from half of planning horizon to the its end. Furthermore, this rate of water supply may be admitted by water utilities, if they accept to cut down or close down supplying water to some specific categories water demands such as unimportant water demands. In other words, the define threshold of overall water supply for the utilities will be above the minimum percentage of water supplied in the UWS.

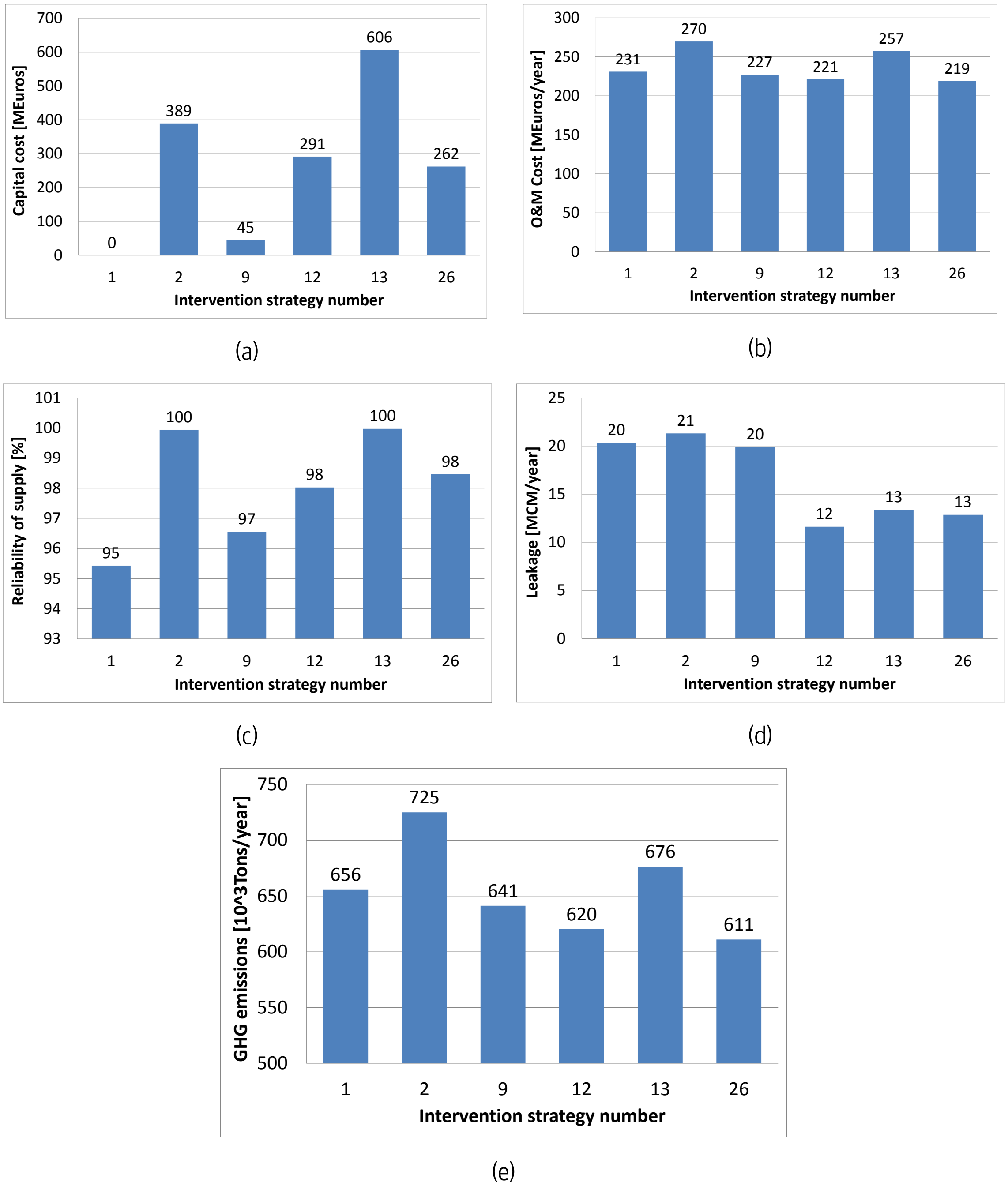


Figure 21: Quantified criteria including (a)total capital cost, (b)Total O&M cost, (c)water supply reliability, (d) leakage, (e)GHG emissions for the select intervention strategies (1,2,9,12,13 and 26)in the period 2011-2040

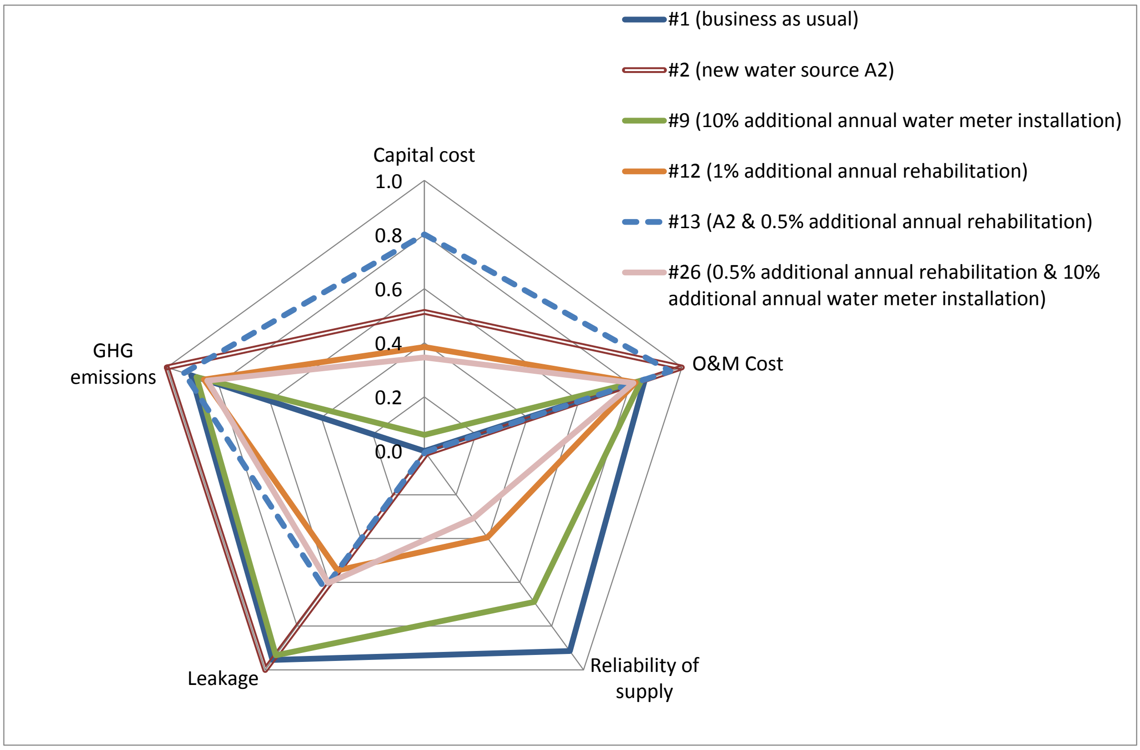
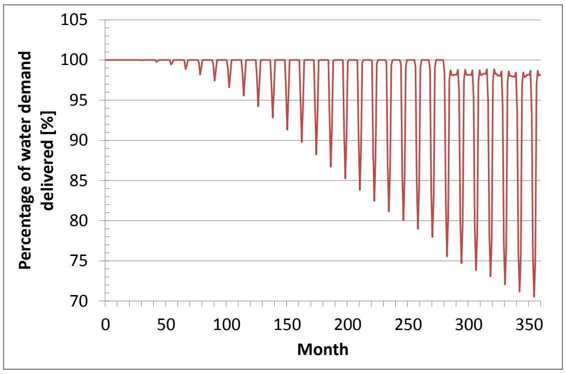
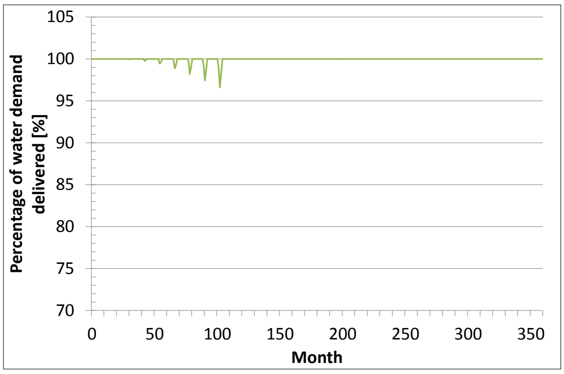


Figure 22: Normalised evaluation criteria of the selected intervention strategies (1, 2, 9, 12, 13 and 26) in Oslo UWS; note that all the criteria are normalised and converted to minimization approach

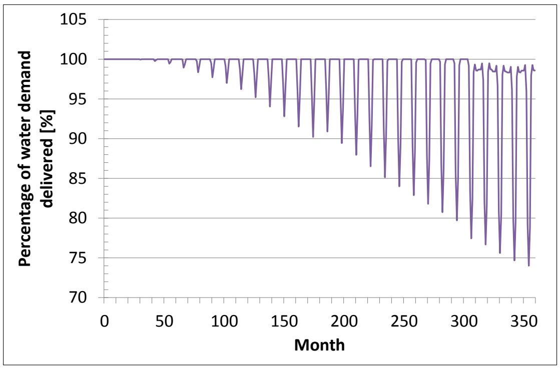
As it can be seen in Fig. 24, the trend of the leakage volume for strategies #1, #2 and #9 is ascending over the planning horizon. In all these strategies, although the water utilities will be carrying out the continuous actions to prevent any increase in the water leakage percentage, the amount of leakage will increase due to increase in population and consequently water demand increase. However, this trend will be descending for the strategies #12, #13 and #26 reinforced by extra annual rehabilitation by water utilities (see Figs. 24d, 24e and 24f). As it can be seen, the average monthly leakage in these strategies will decrease from around 1.2 MCM at 2011 to around 0.5 and 0.6 MCM for 1% and 0.5% additional annual rehabilitation respectively showing 58% and 50% reduction in leakage. Comparing these rates reveals that 0.5% additional annual rehabilitation are more efficient and is able to attain a reasonably closed leakage amount obtained from 1% additional annual rehabilitation with half of the efforts in this regard. However, to find the best rate of additional annual rehabilitation, the consequence of the whole ranges of practical extra annual rehabilitation rates on the leakage reduction needs to be examined.



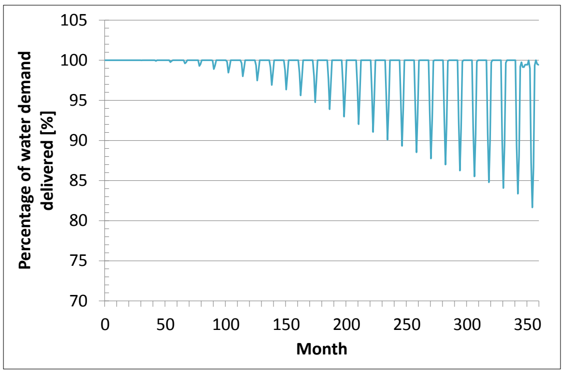
(a) business as usual (strategy #1)



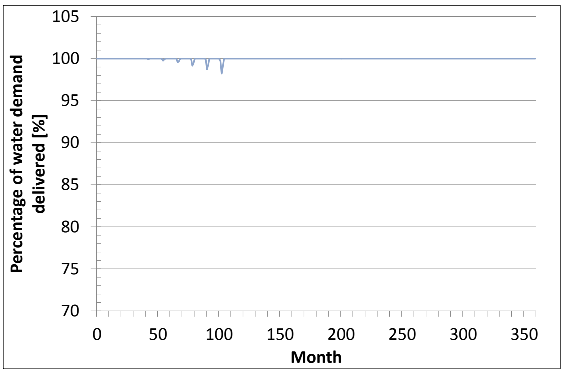
(b) new water resourceA2 (strategy #2)



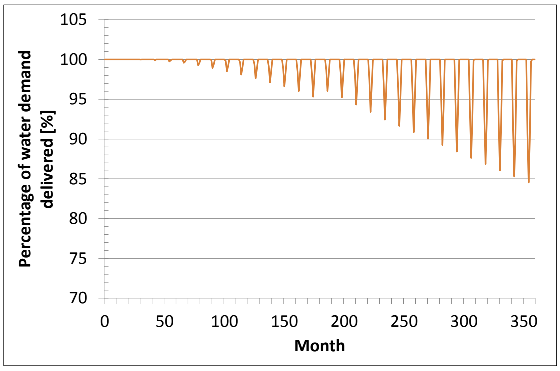
(c) 10% additional annual water meter installation (strategy #9)



(d) 1% additional annual rehabilitation (strategy #12)

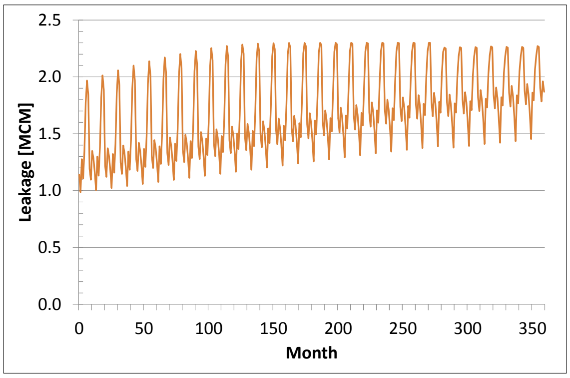


(e) new water resourceA2 & 0.5% additional annual rehabilitation (strategy #13)

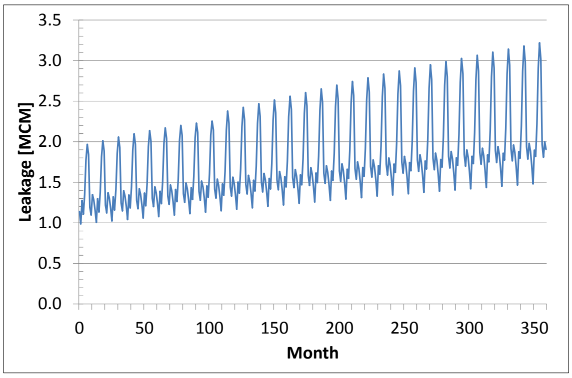


(f) 0.5% additional annual rehabilitation & 10% additional annual water meter installation (strategy #26)

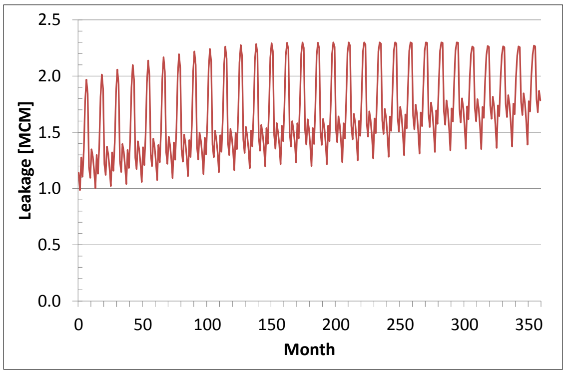
Figure 23: Time series of the percentage of water demand delivered for the select intervention strategies including (a) #1, (b) #2, (c) #9, (d) #12, (e) #13 and (f) #26 n Oslo UWS over the period 2011-2040



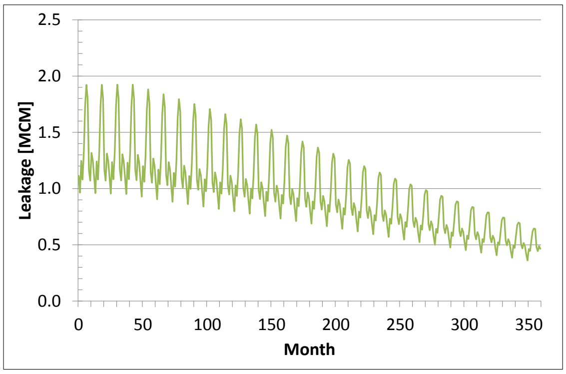
(a) business as usual (#1)



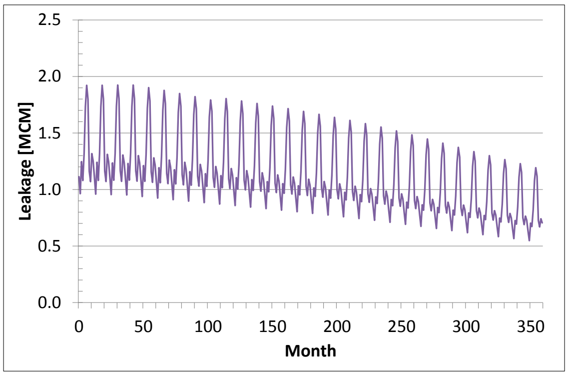
(b) new water resourceA2 (#2)



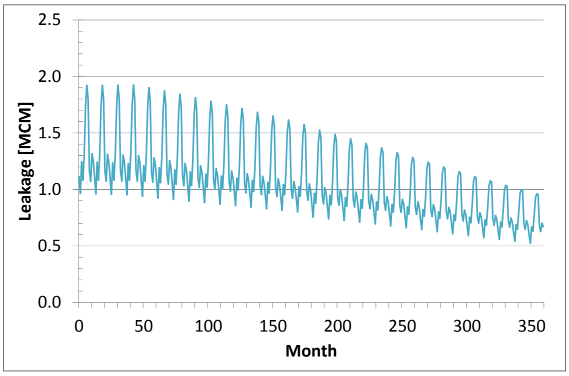
(c) 10% additional annual water meter installation (#9)



(d) 1% additional annual rehabilitation (#12)



(e) new water resourceA2 & 0.5% additional annual rehabilitation(#13)



(f) 0.5% additional annual rehabilitation & 10% additional annual water meter installation(#26)

Figure 24: Time series of the total pipelines leakages of the select intervention strategies including (a) #1, (b)#2, (c)#9, (d)#12, (e)#13 and (f)#26 in Oslo UWS over the period 2011-2040

3.4 Ranking of strategies with respect to all criteria

For a more comprehensive ranking, all strategies need to be rigorously evaluated with respect to the defined qualitative criteria by a number of relevant experts. In this way, various feedbacks from numerous experts will be reflected which in turn enable to combine different approaches to the intervention strategies relative to various qualitative criteria. This can be deemed carefully as the next step of strategies analysis considering the quantitative criteria quantified by the WaterMet^2 model. At the time of writing this report, such a feedback on the qualitative criteria could not be possible. Nevertheless, for illustrative and comparative purposes with the previous ranking result, the strategies were also ranked against qualitative criteria by a relevant expert. Thus, the weighting of this expert for all the strategies with respect to qualitative criteria and the final ranking of the strategies with respect to both quantitative and qualitative criteria are given in Table 14.

Although experts may express different and sometime opposite opinions to intervention alternatives, combined grouping weights can compromise such diversity. The only expert participating in this questionnaire stated the following general attitude for the strategies relative to qualitative criteria when assigning weights to them:

- When considering strategies containing new water resources with respect to company acceptance, option A3 has priority over A2, B3 and C1 due to the fact that A3 involve pipes in an easily accessible tunnel, meaning simplified inspection and maintenance.
- Rehabilitation is regarded positive for both public and company acceptance because it is believed that both leakages and breaks are likely reduced.
- Although water metering may certainly contain an economic benefit, most likely health, public acceptance or company acceptance may not be influenced. There is certain scepticism towards metering in the company, because water metering may give increased costs and maintenance. The public may welcome metering if their costs are reduced, but not if the costs maintain unchanged. Since the total costs for water supply in Oslo will be marginally influenced by the metering, the bills to the public will also be the same. Therefore, the public response to this option can be assumed negative.

When the final ranking in Tables 14 is compared to that in Table 13, the following results can be inferred: (1) the best two ranks in Table 14 are for the higher rate of additional annual rehabilitation (1% and 0.5%) in strategy#12 and #11 as first and second ranks respectively. strategy #12 was also selected as a top rank (2nd rank) with respect to the quantitative criteria; (2) the ranks of the strategies containing water metering has declined in the new ranking owing to inefficiency of water metering based on the expert's belief; (3) in contrary, the strategies with new water sources observed higher ranks in Table 14; (4) the rank of strategies containing additional annual rehabilitation has also increased due to positive approach of the expert; (5) unlike the ranks of the complex strategies without new water resources (#25 - #28) which were amongst the top five ranks in Table 13, they experience a sharp fall in the new ranking except for the rank of strategy #25 which is intact. However, due to the way that qualitative and quantitative criteria values were collected, the ranking results obtained in the case with quantitative criteria only should be trusted more. This can be modified further when more number of experts is involved in the questionnaire for qualitative criteria.

Table 14: Ranking of all intervention strategies with respect to all criteria over the planning horizon

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
Intervention Strategy #1 (business as usual)	0.00	230.93	95.43	20.34	655.92	5.00	5.00	3.00	28
Intervention Strategy #2 (new water source A2)	389.16	269.60	99.94	21.30	724.94	5.00	8.00	6.00	17
Intervention Strategy #3 (Only A3)	479.94	269.60	99.94	21.30	724.94	5.00	8.00	7.00	18
Intervention Strategy #4 (Only B2)	540.21	269.56	99.94	21.30	724.46	5.00	8.00	6.00	22
Intervention Strategy #5 (Only C1)	326.66	269.60	99.94	21.30	724.94	5.00	8.00	6.00	16
Intervention Strategy #6 (only 1% additional annual	9.21	230.60	95.52	20.30	654.61	5.00	5.00	3.00	27

Criteria	*Capital cost*	*O&M Cost*	*Reliability of supply*	*Leakage*	*GHG emissions*	*Health Risk*	*Public Acceptance*	*Company Acceptance*	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
water meter installation)									
Intervention Strategy #7 (only 3% additional annual water meter installation)	27.63	229.95	95.71	20.22	652.00	5.00	5.00	3.00	26
Intervention Strategy #8 (only 5% additional annual water meter installation)	39.35	228.99	96.08	20.09	647.91	5.00	5.00	3.00	24
Intervention Strategy #9 (10% additional annual water meter installation)	45.13	227.18	96.55	19.89	641.26	5.00	5.00	3.00	23
Intervention Strategy #10 (0.2% additional annual rehabilitation)	169.39	223.93	97.29	14.12	630.40	5.00	5.00	4.00	9

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
Intervention Strategy #11 (0.5% additional annual rehabilitation)	216.70	222.87	97.59	13.13	626.45	5.00	6.00	5.00	2
Intervention Strategy #12 (1% additional annual rehabilitation)	291.18	221.19	98.02	11.62	620.22	5.00	7.00	6.00	1
Intervention Strategy #13 (A2 & 0.5% additional annual rehabilitation)	605.86	257.50	99.97	13.37	676.15	5.00	10.00	8.00	7
Intervention Strategy #14 (A3 & 0.5% additional annual rehabilitation)	696.64	257.50	99.97	13.37	676.15	5.00	10.00	9.00	11
Intervention Strategy #15 (B2 & 0.5% additional	756.91	257.46	99.97	13.37	675.71	5.00	10.00	8.00	14

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
annual rehabilitation)									
Intervention Strategy #16 (C1 & 0.5% additional annual rehabilitation)	543.36	257.50	99.97	13.37	676.15	5.00	10.00	8.00	3
Intervention Strategy #17 (A2 & 0.2% additional annual rehabilitation)	558.55	259.08	99.97	14.43	682.64	5.00	9.00	7.00	8
Intervention Strategy #18 (A3 & 0.2% additional annual rehabilitation)	649.33	259.08	99.97	14.43	682.64	5.00	9.00	8.00	13
Intervention Strategy #19 (B2 & 0.2% additional annual rehabilitation)	709.61	259.04	99.97	14.43	682.20	5.00	9.00	7.00	15

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
Intervention Strategy #20 (C1 & 0.2% additional annual rehabilitation)	496.05	259.08	99.97	14.43	682.64	5.00	9.00	7.00	5
Intervention Strategy #21 (A2 & 10% additional annual water meter installation)	434.29	263.72	99.95	20.59	700.14	5.00	7.00	4.00	20
Intervention Strategy #22 (A3 & 10% additional annual water meter installation)	525.07	263.72	99.95	20.59	700.14	5.00	7.00	5.00	21
Intervention Strategy #23 (B2 & 10% additional annual water meter	585.34	263.68	99.95	20.59	699.68	5.00	7.00	4.00	25

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
installation)									
Intervention Strategy #24 (C1 & 10% additional annual water meter installation)	371.78	263.72	99.95	20.59	700.14	5.00	7.00	4.00	19
Intervention Strategy #25 (0.5% additional annual rehabilitation & 5% additional annual water meter installation)	256.05	220.92	98.16	12.99	618.45	5.00	5.00	4.00	4
Intervention Strategy #26 (0.5% additional annual rehabilitation & 10% additional annual water	261.83	218.92	98.46	12.85	611.03	5.00	4.00	3.00	10

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***Health Risk***	***Public Acceptance***	***Company Acceptance***	Rank
Units	MEuros	MEuros/ year	%	MCM/year	10^3Tons/year	-	-	-	
Weights	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Minimisation	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
Normalisation minimum	0.00	0.00	95.00	0.00	0.00	1.00	1.00	1.00	
Normalisation maximum			100.00			10.00	10.00	10.00	
meter installation)									
Intervention Strategy #27 (0.2% additional annual rehabilitation & 5% additional annual water meter installation)	208.75	222.00	97.88	13.97	622.48	5.00	5.00	4.00	6
Intervention Strategy #28 (0.2% additional annual rehabilitation & 10% additional annual water meter installation)	214.52	220.07	98.24	13.82	615.39	5.00	4.00	3.00	12

4 Summary and Conclusions

The Oslo UWS which may be facing a problem of supply/demand balance in the future was analysed in this case study. The water supply problem is mainly due to fast population growth expected from now until 2040. To address this issue, the WaterMet^2 model of the Oslo UWS was developed first. The 28 optional intervention strategies were then identified based on the three different types of interventions considered: (1) new water resources; (2) additional annual water meter installation; and (3) increased annual rate of pipeline rehabilitation. The single scenario analysed assumes the fast population growth and normal availability of water at sources over the aforementioned planning horizon. The analysed intervention strategies were evaluated and ranked using multiple criteria, both quantitative and qualitative. The quantitative criteria were: (1) water supply reliability; (2) average annual leakage; (3) total capital cost; (4) average annual cost; (5) average annual GHG emissions; and the qualitative criteria were: (6) Health risks; (7) Social acceptance and (8) Company acceptance.

The above analyses were performed in two stages. In the first stage, different types of intervention options were examined only. In the second stage, more complex intervention strategies were formed by combining promising individual options from the first part of the analysis. Once this was done, all 28 intervention strategies considered were evaluated in terms of multiple criteria by performing a number of respective WaterMet^2 model runs. The criteria values obtained this way were then used to rank the intervention strategies analysed by using the Compromise Programming MCDA method.

The ranking results obtained with respect to quantitative criteria show that the four out of five top ranks belong to the strategies which combine various levels of additional annual pipeline rehabilitation and water meter installation. Moreover, the intervention strategies formed on the basis of adding new water resources and WTWs only seem inefficient when compared to others, mainly due to the huge capital costs required to realise these schemes. These ranks were displaced when qualitative criteria were also involved based on the expert's opinion. However, due to the way that qualitative and quantitative criteria values were collected currently, the ranking results obtained by using quantitative criteria only should be trusted more. This evaluation against the qualitative criteria can be further modified by a number of relevant experts in order to obtain a more comprehensive ranking of the strategies.

This ranking is used for illustration purposes only with the aim to demonstrate the results obtained by using the WaterMet^2 model and the DSS tool that will be developed in WP54. These results although show some potential and promising strategies but cannot be fully trusted at the moment nor should be used to make any real decisions. To obtain a robust solution, the current WaterMet^2 model still needs to be further developed, tested and evaluated for multiple future scenarios and risk type criteria calculated by the risk model developed in WP32.

5 References

Andre´ F.J., Romero C. (2008). Computing compromise solutions: On the connections between compromise programming and composite programming, Applied Mathematics and Computation 195, 1–10.

Behzadian,K., Kapelan,Z., Rozos,E., Makropoulos, C., (2012). "WaterMet^2 model functional requirements", TRUST, WA3.3.

Behzadian, K., Kapelan, Z., Rozos, E., Makropoulos, C., (2012). "Deliverable D33.1: WaterMet^2 conceptual model report", TRUST.

Brattebø, H., Sægrov, S., and G Venkatesh (2011). "Metabolism modelling of urban water cycle systems system definition and scoping report", TRUST, Internal deliverable, WA 3.3.

Comox valley record (2011), twice-weekly community newspaper, http://www.comoxvalleyrecord.com/lifestyles/157947255.html, British Columbia, Accessed several times in 2011-2012.

Oslo Water (2011a) "Rough Analysis of Alternatives" translated from the original Norwegian version to English by G Venkatesh (NTNU) and 'Water Treatment Plant Bulletin' by Oslo Water.

Oslo Water (2011b) "Forecast of Water Usage in the Future in Oslo" translated from the original Norwegian version to English by G Venkatesh (NTNU) and 'Water Treatment Plant Bulletin' by Oslo Water.

Southern water, UK (2011). http://www.southernwater.co.uk/for-business/your-water/water-meters/survey-and-installation-costs.asp , Accessed several times in 2011.

Ugarelli, R., G Venkatesh, H Brattebø, S Saegrov (2008). Importance of investment decisions and rehabilitation approaches in an ageing wastewater pipeline network. A case study of Oslo (Norway). Water Science and Technology, 58 (12), 2279–2293.

Venkatesh G. (2012). Cost-benefit analysis – leakage reduction by rehabilitating old water pipelines: Case study of Oslo (Norway), Urban Water Journal, 9:4, 277-286 http://dx.doi.org/10.1080/1573062X.2012.660960

Yu P. L. (1985). Multiple-Criteria Decision Making: Concepts, Techniques, and Extensions, Plenum Press, New York.

6 Appendices

6.1 Appendix A: Embodied energy

Embodied energy and associated GHG emissions are presented for two categories of materials and chemicals. In the WaterMet[2] model, materials will be used in pipeline rehabilitations and chemicals will be used in WTWs.

Table A.1: Embodied energy and associated GHG emissions in chemicals

Name of chemicals	*Embodied energy (kWh/kg)*	*GHG emissions (kg CO2-eq/kg chemicals)*
Alum ($AL_2(SO_4)_3$)	0.9	0.1674
Carbon dioxide (CO_2)	1.4	0.2604
Calcium hydroxide ($Ca(OH)_2$)	1.0	0.186
PAX	2.8	0.5208
Sodium hypochlorite (NaoCl)	1.43	0.26598
Chlorine	2.0	0.372
Iron chloride	0.9	0.1674
Iron sulphate	1.0	0.186
Nitric acid	1.4	0.2604
Methanol	2.0	0.372

Table A.2: Embodied energy and associated GHG emissions in materials

Name of chemicals	*Embodied energy (kWh/kg)*	*GHG emissions (kg CO2-eq/kg material)*
PVC pipe	23.6	2.36
PE pipe	23.6	2.33
Mild steel pipe	26.7	6.5
Ductile iron pipe	10.6	3.4
Grey cast iron pipe	6.9	3.34
Concrete	0.6	0.23
Epoxy resin	6.4	6.7
Polyurethane	5.0	4.3

6.2 Appendix B: Energy cost and GHG emissions

The cost of energy in the form of either electricity or fossil fuel, which will be used in the WaterMet^{2}model is given in Table B.1 as well as the associated GHG emissions.

Table B.1: Cost and GHG emissions of energy sources

Name of energy source	*Cost*	*GHG emissions*
Electricity	0.0854 (Euro/kWh)	0.54 (kg CO2-eq/kWh)
Fossil fuel (diesel)	1.15 (Euro/Litre)	2.331 (kg CO2-eq/Litre)

6.3 Appendix C: Specification of rehabilitation methods

In the WaterMet^2 model, the cost and diesel consumption for one of four specified rehabilitation methods (slip-lining with PE pipe) will be provided as given in Table C.1 (Venkatesh, 2012, Ugarelli, R., et al. 2008). Total GHG emissions resulted from this rehabilitation method comprise direct GHG emissions from diesel consumption and indirect GHG emissions from using PE pipe for rehabilitation. For calculating the mass of the consumed PE pipe, it is assumed that specific gravity of PE is equal to 920 kg/m^3 and the thickness chosen for PE pipe is equal to internal diameter of the pipe rehabilitated multiplied by 0.09. The respective cost and GHG emissions for other methods are given in Table C.2 as a coefficient of the cost and GHG emissions of the method of slip-lining with PE pipe. The contribution of each of four rehabilitation methods towards the total annual rehabilitation is given in Table C.2.

Table C.1: Cost and GHG emissions for rehabilitation method of slip-lining with PE pipe (Venkatesh, 2012)

Size of pipeline	*Total cost (Euro/m)*	*Diesel consumption (Litre/m)*
Small-size pipeline (diameter<249 mm)	275	1.0
Medium-size pipeline (250 mm<diameter<449 mm)	526	1.5
Small-size pipeline (500 mm<diameter)	1242	2.0

Table C.2: Contribution of different rehabilitation methods along with the associated cost and GHG emissions

Method of rehabilitation	*% of total annual rehabilitation*	*Cost (coefficient of the cost for slip-lining with PE pipe)*	*GHG emissions (coefficient of the GHG emissions forslip-lining with PE pipe)*
lining with polyurethane (PU)	40	0.5	0.5
slip-lining with PE pipe	20	1	1
pipe cracking + lining	20	1.5	1.5
rebuilding with ductile iron pipe	20	5	10