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Urban water system metabolism assessment using WaterMet^2 model

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Abstract

This paper presents a new "WaterMet^2" model for integrated modelling of an urban water system (UWS). The model is able to quantify the principal water flows and other main fluxes in the UWS. The UWS in WaterMet^2 is characterised using four different spatial scales (indoor area, local area, subcatchment and system area) and a daily temporal resolution. The main subsystems in WaterMet^2 include water supply, water demand, wastewater and cyclic water recovery. The WaterMet^2 is demonstrated here through modelling of the urban water system of Oslo city in Norway. Given a fast population growth, WaterMet^2 analyses a range of alternative intervention strategies including 'business as usual', addition of new water resources, increased rehabilitation rates and water demand schemes to improve the performance of the Oslo UWS. The resulting five intervention strategies were compared with respect to some major UWS performance profiles quantified by the WaterMet^2 model and expert's opinions. The results demonstrate how an integrated modelling approach can assist planners in defining a better intervention strategy in the future.

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*Keywords:*Urban water system; simulation; WaterMet^2; performance; criteria; strategy; MCDA

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1. Introduction

One of the conventional approaches to model an urban water system (UWS) is to use a physically based model to simulate a hydraulic behaviour of the UWS and to identify water quality characteristics. However, physically based models are typically sophisticated and very detailed models which need a lot of input data which are demanding and tedious for many case studies. In addition, these models usually can only simulate a part of the UWS. In contrast, conceptually based models with the ability of quantifying flow paths and contaminant loads in an UWS enable understanding of the impacts of the interaction of water within an integrated urban water management systems where potable water, stormwater and wastewater need to be considered together.

Some of the instances of these conceptually based models have been developed in the past such as AQUACYCLE (Mitchell et al. 2001),UWOT (Makropoulos et al. 2008),UVQ (Mitchell and Diaper 2010) and City Water (Mackay and Last 2010). These scoping models aim to simulate the integrated water system within an urban area and estimates the contaminant loads and the volume of the water flows throughout the UWS, from source to discharge point. Such a simulation enables the planners to explore a wide range of conventional and emerging techniques in water supply, stormwater and wastewater services to an UWS.

Despite plethora of studies modelling integrated urban water systems, those start potable water from the point where it is delivered to households by water service provider. Therefore, potable water is modelled as an external supply and its demand is calculated as the sum of the neighbourhood demands that are not met by local or decentralised supply schemes (Mackay and Last 2010). The present work strives to extend the modelling of potable water to water resources and integrates it with other components in water supply, sewerage and drainage systems. This is handled through a simplified and integrated approach for modelling water distribution and wastewater systems. Then, the physical metabolism of this integrated UWS is quantified through some key performance indicators covering all sustainability related issues (environmental, economic and social). All this, in turn, will enable the planners to assess the impact of a combination of future intervention strategies including technologies and their operation on different parts of the UWS.

The work presented here is a part of EU FP7 TRansition to Urban water Services of Tomorrow (TRUST) project in which a conceptually based model known as 'WaterMet^2' has been developed for a generic city. The main purpose of the WaterMet^2 model is to develop an UWS simulation model which will be a part of a Decision Support System (DSS) to quantify the impact of different interventions/technologies on the UWS performance, including associated risks and costs. Despite this, the WaterMet^2 model itself is a standalone piece of software which runs in a Windows™ screen with the capability of navigational devices to build a new UWS model.

2. WaterMet^2 Modelling Concept

The WaterMet^2 model is a conceptual, simulation type, mass balance based and integrated UWS model which quantifies the metabolism-related performance of a generic UWS with focus on sustainability related issues (Behzadian et al. 2012a). Metabolism in an UWS is referred to the flows and conversion processes of all kinds of water flows, materials and energy in the UWS to fulfill the necessary functions (Brattebø et al. 2011, Venkatesh and Brattebø 2011). The integrated modelling of the UWS implies the whole processes and components in an urban area related to any kind of water flows as a complex and interrelated system. All this, in turn, will enable quantifying a number of different indicators related to performance, risk and cost over some planning horizon.

The main flows and storages modelled in the WaterMet^2 are illustrated in Fig. constituting four main subsystems as (Behzadian et al. 2012b): (1) water supply comprising three storages (i.e. water resources, Water Treatment Works (WTWs) and service reservoirs) and three types of water flow 'routes' connecting the storages to each other (called as water supply conduits, water trunk mains, and distribution networks); (2)water demand comprising storages for all water consumption points including indoor and outdoor water usages. The water demand for consumers can be calculated based on the user specified method (e.g. appliances and fittings or water demand per capita); (3) wastewater including two storages (separate/combined sewer systems and Waste Water Treatment Works (WWTWs)); (4) cyclic water recovery including both centralised and decentralised cyclic water recovery systems.

The WaterMet^2 model quantifies several principal flows in the UWS components as: (1) water flow including clean (potable) water, stormwater, grey water, black water (Makropoulos et al. 2008); (2) energy flux either consumed in various forms (i.e. electricity, fossil fuel, embodied energy) or generated as heat or electricity; (3) greenhouse gas emission (GHG) flux generated either directly (from electricity or fossil fuel consumptions) or indirectly as embodied GHG (from materials used in pipeline rehabilitations and chemicals used/produced in water and wastewater treatment operations); (4) chemical flux consumed for water treatment in WTWs, service reservoirs and WWTWs; (5) pollutant flux resulted from tracking down pollutant loads in wastewater and cyclic water recovery subsystems.

2.1. Spatialand Functional UWS Representation

The spatial limit of the UWS is defined for the administrative city limits of an urban water utility. The WaterMet^2 Model recognises four spatial scales representing the whole urban water system as: (1) indoor area; (2) local area; (3) subcatchment area; and (4) city area. The specifications and functional processes modelled at each scale are briefly outlined here.

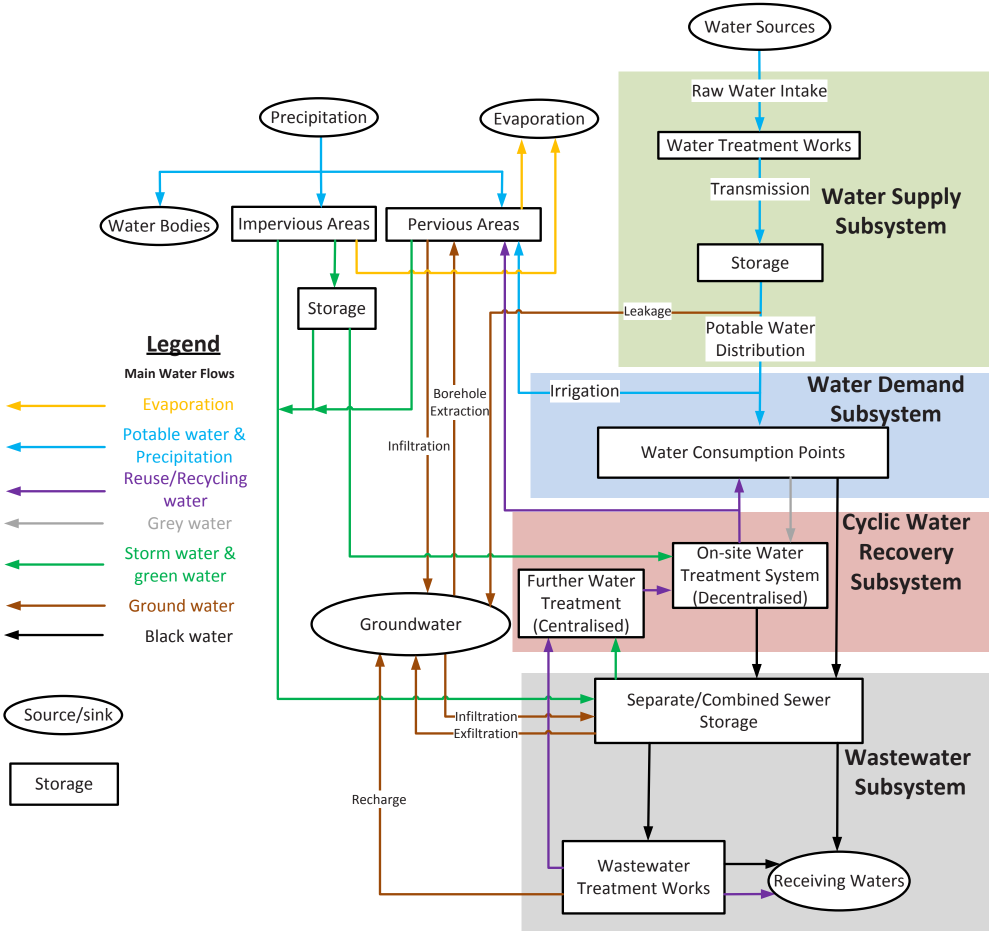

Fig.1.Main flows and storages in the WaterMet^2 model

Indoor area is the smallest spatial scale of the UWS in the WaterMet^2 model to represent a single specifically household without any surroundings (e.g. garden or public open space representing any outdoor area). This area is not necessarily limited to a residential area, but it can be used for any type of property (e.g. residential, industrial, commercial, public, etc.). The main functional process of this level is the definition of water demand which is characterised based on either daily average water demand per capita or detailed information of the water consumption for residential appliances and fittings (i.e. hand basin, bath and shower, kitchen sink, dish washer, washing machine and toilet). The information for the latter is specifically required when applying some interventions such as various demand management schemes (and many other).

Local area is defined in the WaterMet^2 as a group of similar typical households/properties (indoor areas) with a surrounding area. In addition to the water demand specified in an indoor area, other types of water demands (e.g. irrigation, industrial/commercial, frost tapping and unregistered public use) are defined here, based on average daily consumption per local area. The main processes and components modelled only at this level are rainfall-runoff modelling and local rainwater harvesting and grey water recycling systems. In addition, temporal water demand variations (i.e. seasonal and annual) for all water demand types are specified at this level.

Subcatchment area is used model to represent a group of neighbouring local areas in the WaterMet^2. The WaterMet^2 subcatchments are defined originally based on the urban drainage system considerations (i.e. topology and gravity in stormwater/wastewater collection systems). The choice of subcatchment and local area size is dependent on a number of factors such as city size, level of spatial resolution required, type of intervention modelling, and available data in subcatchments. Larger, more centralised rainwater harvesting and grey water recycling systems are modelled at this spatial level.

City/UWS area is the highest spatial level of UWS modelling in the WaterMet^2. This area is characterised as a number of subcatchments along with other main components modelled only at this level. These components are raw water resources, water supply trunk mains, WTWs, service reservoirs, principal mains in a water distribution system, separate/combined sewer system, and WWTWs. The WaterMet^2 model at this level recognises a simplified and integrated approach outlined below for modelling water supply and wastewater systems.

The simplified potable water supply system in the WaterMet^2 comprises four 'storage' nodes interconnected by three types of water flow 'routes'. The storages are water resources, WTWs, service reservoirs and subcatchments and the routes are water supply conduits between water resources and WTWs, water trunk mains between WTWs and service reservoirs, and distribution networks between service reservoirs and subcatchments. The potable water demand for each subcatchment is calculated as the sum of the potable water demand nodes located in the local areas of the subcatchment that are not met by cycling water recovery (centralised and decentralised water demand schemes) (Mackay and Last 2010). Potable water demand of each subcatchment is met by interconnected service reservoirs based on the pre-defined proportions. The, the delivered water demand of the subcatchment is further split and allocated among the local areas in the subcatchment. Further, wastewater and stormwater generated in the local areas of the subcatchment are aggregated and represented as wastewater/stormwater of the subcatchment and start point in the simplified wastewater system. This system comprises three key 'storage': separate/combined sewer system interconnecting between subcatchments themselves or between subcatchment and WWTWs, WWTWs and receiving waters (only as 'sink' points). Stormwater/wastewater exceeding the daily transmission/storage capacity of sewer systems overflow through combined sewer overflow (CSO) and storm tank overflow (STO) structures into receiving waters.

As the metabolism WaterMet^2 model aims to support strategic planning level, a daily time step selected by previous works (Mitchell and Diaper 2010, Makropoulos et al. 2008, Mackay and Last 2010) is adopted here as an appropriate simulation interval and the smallest temporal scale. The daily time step will be aggregated to simulate the UWS performance for a period of *N* years specified by the user.

3. Case Study

3.1. Problem description

The application of the WaterMet^2 model is demonstrated here on the problem of long-term planning for the urban water system of Oslo city in Norway. Oslo city is facing some challenges in the future mainly due to climate change, population growth, increasing urbanization and ageing infrastructure. All these are expected to impose significant strains on the Oslo UWS. The Oslo Water and Sewerage Works (Oslo VAV) is a public utility supplying water and wastewater services. Moving along the path towards sustainability poses new challenges and demands for the utility. A brief description of Oslo water system and options for resolving the potential problems are briefly outlined here. Additional details can be found in Behzadian and Kapelan TRUST project report (2012).

Two main raw water resources each with the corresponding WTWs are currently available to supply fresh water to the city of Oslo with 90% and 10% of total supply capacity (Oslo VAV2011a and b). Both water resources on which the city of Oslo relies are of limited capacity (60 and 13.8 million cubic metres (MCM)) and inflow (287 and 12 MCM/year). Two potential water resources including a lake and a river with high capacities (lake with the total volume of over 13,000 MCM and river with annual average flow of 22,000 MCM) are envisaged for the future water supply of Oslo city. For water supply from either of them, two new WTWs would also need to be built. Currently, the Oslo UWS has a mix of combined and separate sewer system (specifically, out of total length of sewers 37% is combined sewers, 30% sanitary sewers and 33% storm drains) and two WWTWs collecting 63 and 27 per cent of wastewater from the wastewater flow (Oslo VAV 2006).

To address capacity-limitation of two existing water resources the daily time series of the last 30 years inflows (1981-2010) into these water resources are selected and assumed to be the time series of inflow over the 30 year planning horizon (2011-2040).

Oslo UWS model is represented here as an aggregated model by using a single WaterMet^2 subcatchment with a single local area used to define future water consumption. The total number of properties in Oslo city is 320,000 with a population of 624,000 in 2011.

Water demand of the local area is split into domestic, industrial, irrigation, frost tapping and unregistered public use (Oslo VAV2011a and b). Domestic (indoor) water demand per capita is assumed to be 160 L/day. Seasonal variations are defined for some categories of water demand in Oslo. More specifically, irrigation of gardens and public green areas from the water supply system is carried out from the middle of May to the end of August. To prevent winter frost damage, frost tapping is performed from November to March by allowing water to flow continuously at a minimum rate (Oslo VAV 2006, Oslo VAV2011b). It is assumed that these variations are consistent over the whole planning horizon. In contrast, it is assumed that domestic and industrial water demands have no seasonal variations. The annual increase of water demand for domestic, industrial and plant irrigation in Oslo is assumed based on the envisaged fast growth of population over the planning horizon whilst no annual changes are assumed for frost tapping over this period (Oslo VAV2011b).

The whole database of the water supply pipelines containing the attributes of 28,442 pipes with lengths greater than 10 metres (i.e. material type, length, diameter and age) is assumed in the single WaterMet^2 subcatchment. The pipelines connecting the single subcatchment to the two WTWs in the Oslo UWS are split into two parts sharing 90% and 10% of the subcatchment water demand. The existing leakage from the subcatchment pipelines is assumed to be 22% of total water demand.

The only scenario considered here assumes highest rate of water demand as a consequence of the highest population growth projection over the planning horizon.

3.2. Intervention strategies

The alternative UWS intervention strategies here can be envisaged as a combination of five individual options assessed against the 30 year planning horizon (2011-2040). These individual options are: (1) new water resources; (2-3) water demand management schemes by installing additional water meters for households or increase in the annual existing rate of pipeline rehabilitation; and (4-5) water saving options by introducing rainwater harvesting (RWH) or grey water recycling (GWR) systems. In the present work, only the following intervention strategies are defined and assessed in Oslo UWS as a sample of either simple or complex strategies to illustrate the capabilities of the WaterMet^2 to support the integrated urban water management options:

- Strategy#1: business as usual (BAU) strategy: it resembles 'do nothing' for the UWS over the planning horizon and implies as a benchmark strategy;

- Strategy#2: addition of a new water resource along with two WTWs starting from 2020: It considers option A2 out of the four final options in the relevant report for adding new water resources (Oslo VAV 2011a, Behzadian and Kepelan 2012).
- Strategy#3: 1% increase in the rate of annual pipeline rehabilitation starting from 2015: it is assumed that the current annual rate of pipeline rehabilitation (i.e. 1% of the total length of water supply pipelines in the Oslo UWS) will be increased by 1% from 2015. Therefore, the new annual rate of pipeline rehabilitation will become a constant amount of 2% of total length in the water supply pipelines. Note that 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. It is also assumed that decrease in the pipeline leakage happens when additional annual rehabilitation is applied and its amount is proportional to the length and age of rehabilitated pipes (Venkatesh 2012). In this case, once the increased rehabilitation is carried out, the cost and the associated GHG emissions are calculated based on total cost of the materials and diesel fuel consumed for rehabilitation (Ugarelli et al. 2008).
- Strategy#4: 0.5% increase in the rate of annual pipeline rehabilitation plus 10% additional annual water meter installation starting from 2015: it can be thought that a lower level of additional rate of annual rehabilitation can be combined with another intervention to create a new efficient intervention strategy. Therefore, it is assumed that from 2015 the new annual rate of pipeline rehabilitation will become a constant amount of 1.5% of total water supply pipeline length and water metering coverage of customers will increase annually by installing 10% additional water meters (constant percentage of total) for domestic customers in households where water is not metered. It is assumed that no water meters are installed for domestic customers at year 2010 (Comox 2011). Note that 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 VAV 2011b).
- Strategy#5: addition of RWH and GWR systems at local level: As another thought of a combined strategy is to define GWR and RWH systems at local level together. Therefore, this strategy is defined as a combination of one RWH and GWR systems representing all many small water treatment units across the city assuming that they are adopted by 50% of households. Given that 3 m^3 is sufficient for the tank capacity of a household RWH system with the capital and operational costs equal to 530 and 24 Euro/m^3 respectively (Ward et al. 2010, 2012), the total volume of the single represented RWH tank is 0.48 MCM. Similarly, the size of the represented GWR system is assumed to be 39,000 m^3 with EUR 59 million and EUR 1.5 million/year for capital and operational cost respectively (Memon et al. 2005). It is assumed that RWH system collects runoff from roofs, roads and pavements and GWR system collects grey water from hand basin, shower, frost tapping. Then it is assumed that both RWH and GWR systems supply water demands for toilet flushing, irrigation and industrial usages. The electricity consumption of RWH and GWR systems is assumed to be 0.54 and 1.84 kWh/m^3 respectively (Ward et al. 2011, Memon et al. 2005).

3.3. Evaluation criteria

The evaluation criteria should cover the different dimensions of sustainability in the UWS in response to social, environmental and economic aspects. Here, the following seven criteria including six quantitative criteria and one qualitative criterion are used to compare, evaluate and rank among the intervention strategies. The quantitative criteria will be quantified by the WaterMet^2 model whilst the only qualitative criterion will be quantified by experts' opinions and judgements.

1. Present value of total capital costs: once interventions related to the strategies are applied in the Oslo UWS, the associated capital investments are discounted in year 2011 with 3% discount rate.

2. Present value of total O&M costs: both fixed and variable costs related to different components in the UWS and applied over the planning horizon are discounted in year 2011. Note that the fixed costs refer to the labour and maintenance costs which are constant over a year in a component such as water resources, WTWs and etc. The

variable costs refer to those operational costs which are dependent on the amount of water consumed such as electricity and fossil fuel per cubic meters used.

3. Reliability of water supply: ratio between total water delivered to customers and total water demand over the planning horizon.

4. Total water leakage: sum of the leakage volume in water distribution systems with respect to the degree of pipeline rehabilitation during the planning horizon.

5. Total GHG emissions: both types of direct GHG resulted from electricity and fossil fuel; and indirect GHG resulted from embodied energy over the planning horizon of the UWS.

6. Total volume of annual average CSOs: the annual average of the CSO volume from both sewer system and WWTWs over the planning horizon.

7. Social acceptance of demand management schemes: it refers to which extend an intervention strategy is supported by the society especially water consumers in order to fulfill the water demands. This criterion reflects the support and willingness of the water users from a strategy with respect to a number of factors such as water quality and interruption to supply issues which can have a direct effect on their lives.

4. Result and discussion

The WaterMet^2 model for Oslo was developed and calibrated for the existing conditions in the Oslo UWS. The calibration of the WaterMet^2 model parameters was carried out based on historical daily measurements of water production at WTWs, wastewater treated at WWTWs and daily CSOs occurring in the UWS in the time period between 2009 and 2010 as well as annual principal data flows from Excel metabolism model developed by Venkatesh et al (2012).

Due to the population growth and subsequently increase in water demands, BAU strategy is unable to completely supply potable water demand over the planning horizon. Figure 2 shows the total amount of annual potable water undelivered starting from 2018 and will expand rapidly over the following years of the planning horizon. This figure also depicts the share of the components contributing to this shortage. In particular, the majority of potable water shortage is attributed to insufficient capacity at WTWs (86%) whilst contribution of insufficient water resources at source is only 13% as water shortage which mainly occurs over the last 7 years of the planning horizon. Note that the undelivered water demand related to lack of conveying capacity in the distribution system is rather negligible (1%).

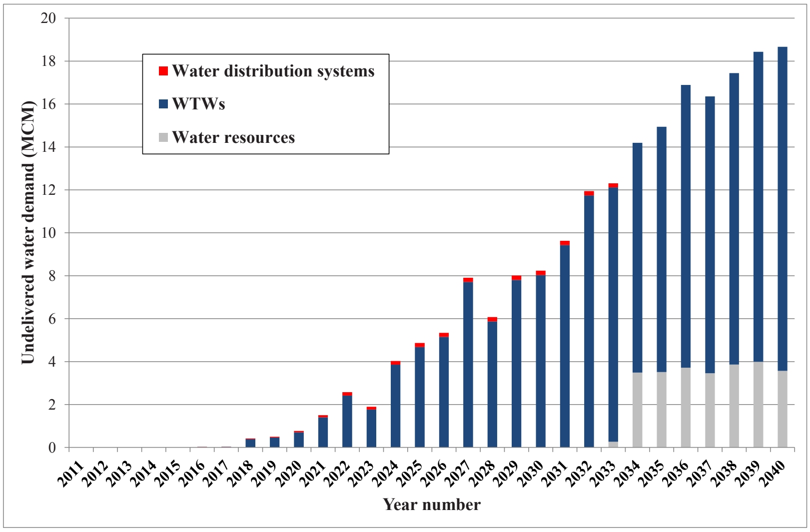

Fig. 2.Undelivered water demand in water supply components over the planning horizon

Table 1 shows the evaluation of the five intervention strategies against the criteria. The quantitative criteria are evaluated by running the WaterMet^2 model. The only qualitative criterion (social acceptance) is quantified by expert's opinions though rating on a scale of 1 to 10 in which 1-2, 3-4, 5-6, 7-8 and 9-10, represent extremely low, low, medium, high and extremely high social acceptance, respectively. Note that the qualitative criterion needs to be rigorously evaluated against all strategies by a number of relevant experts to combine different approaches to that qualitative criterion. As the access to those relevant experts could not be possible at the time of this analysis, this was done by only one expert for illustrative and comparative purposes.

In order to compare the intervention strategies, they are ranked by using a Compromise Programming (CP) MCDA method (Zeleny 1973) with respect to the evaluation criteria. 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). 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 1. Note that the results of the ranking shown here are for illustrative purposes in order to represent the type of the post-analysis which can done by using the WaterMet^2 model.

For comparison between intervention strategies, the relative values of the quantified evaluation criteria (the real value divided by the highest value for each criterion shown in Table 1) are shown in Figure 3. As it can be seen in the figure, each intervention strategy relative to the BAU could gain some noticeable enhancement. In particular, the water supply reliability increased from 94% in the BAU strategy to 100% when adding new water sources (strategy #2). The reliability can improve up to 98% once a combination of other interventions other than new water resource is implemented. However, increased reliability of water supply is achieved at the cost of large capital investment required for building new water resources and associated WTWs or less expensive strategies (#3-5). Likewise, the O&M costs in strategy #2 are significantly high compared to other strategies (#3-5). As these strategies (#3-5) aim to reduce overall water demands, a substantial reduction in the leakage has also occurred. More specifically, the strategies containing additional annual rehabilitation (#3-4) directly target on lowering leakage whilst GWR and RWH systems indirectly decrease (#5) leakage by reducing potable water consumption. The additional benefit of using RWH system in strategy #5 is 32% reduction in the volume of annual CSOs which is a consequence of reduced runoff entering the combined sewer system. This can be attributed to the RWH tank which causes the attenuation of runoff volume. Figure 4 shows the variation of total volume of annual CSOs between strategies #1 (BAU) and #5 (RWH and GWR systems). As it can be seen, the attenuation of CSOs volume starts from 2015 when the intervention strategy is implemented. This can confirm the effectiveness of using both RWH and GWR as a promising option and efficient strategy in both water supply and wastewater systems.

Table 1.Ranking of intervention strategies with respect to evaluation criteria over the planning horizon

Criteria	***Capital cost***	***O&M Cost***	***Reliability of supply***	***Leakage***	***GHG emissions***	***CSO volume***	***Social acceptance***	***Rank***
Units	Million Euro	Million Euro/year	%	MCM/ year	10^3Tons/ year	MCM/ year	-	
Strategy #1 (business as usual)	0	58	94	20	76	5.9	8	4
Strategy #2 (additional water source)	401	87	100	22	78	5.9	7	5
Strategy #3 (1% additional annual rehabilitation)	265	58	97	13	75	5.9	6	1
Strategy #4 (0.5% additional annual rehabilitation & 10% additional annual water meter installation)	264	58	98	14	73	5.7	5	2
Strategy #5 (RWH and GWR systems)	278	67	98	17	73	4.0	3	3

The above analysis should be used for illustrative purposes only, i.e. no intervention strategy shown here should be treated as a real-life solution. Additional work is currently performed to refine the WaterMet^2 model and to analyse additional / more detailed intervention strategies with the aim to quantify their impacts on the long-term performance of the Oslo VAV system in terms of additional evaluation criteria.

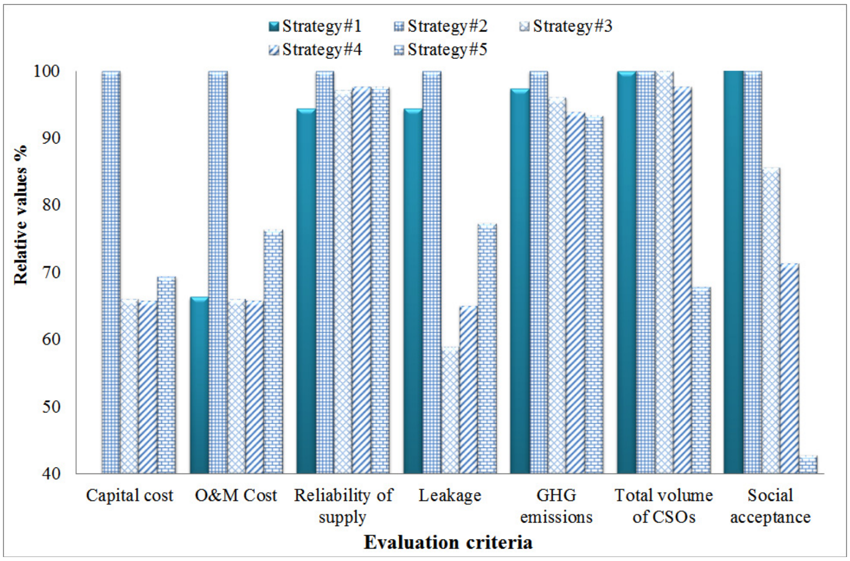

Fig. 3.Relative values of the quantified evaluation criteria (real values divided by the highest value of each criterion) for intervention strategies

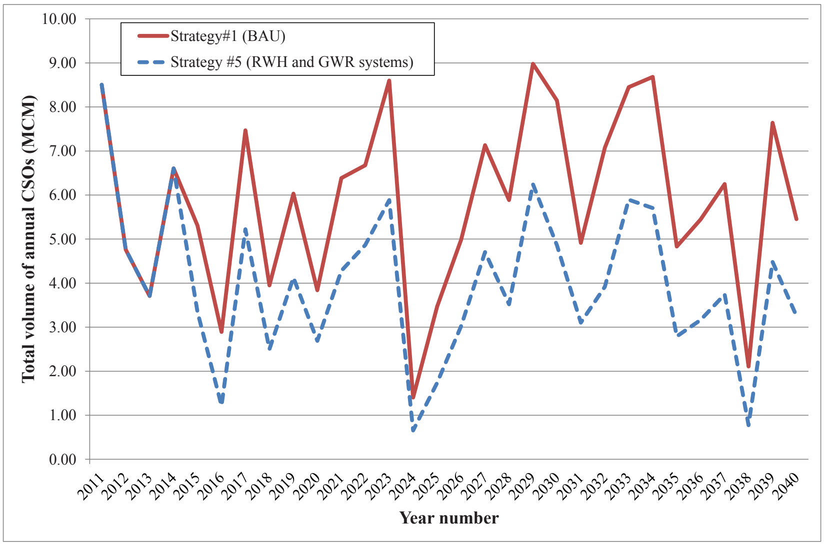

Fig. 4.Variation of total volume of annual CSOs between strategies#1 (BAU) and #5 (RWH and GWR systems)

5. Conclusion

The Oslo UWS facing a problem of supply/demand balance due to fast population growth in the future was analysed in this paper. To address this issue, the WaterMet^2 model of the Oslo UWS was first developed and calibrated. Five individual interventions were identified to organise five intervention strategies as either simple or complex. These intervention strategies were then compared with seven quantitative and qualitative criteria. Both quantitative and qualitative criteria evaluated by WaterMet^2 and expert's opinions respectively were then used to rank the intervention strategies by using the Compromise Programming MCDA method. The strategy including RWH and GWR systems showed to be promising interventions as they can improve performances of both water supply and wastewater systems in the Oslo UWS. This ranking is used for illustrative purposes only with the aim to demonstrate the results obtained by using the WaterMet^2 model. Although the results show some potential and promising strategies, they cannot at the current stage of work 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. The results obtained demonstrate how an integrated modelling approach such as WaterMet^2 can be used to assist planners in defining the best future intervention strategy.

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