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WaterMet^2: a tool for integrated analysis of sustainability-based performance of urban water systems

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Abstract. This paper presents the "WaterMet^2" model for long-term assessment of urban water system (UWS) performance which will be used for strategic planning of the integrated UWS. WaterMet^2 quantifies the principal water-related flows and other metabolism-based fluxes in the UWS such as materials, chemicals, energy and greenhouse gas emissions. The suggested model is demonstrated through sustainability-based assessment of an integrated real-life UWS for a daily time-step over a 30-year planning horizon. The integrated UWS modelled by WaterMet^2 includes both water supply and wastewater systems. Given a rapid population growth, WaterMet^2 calculates six quantitative sustainability-based indicators of the UWS. The result of the water supply reliability (94 %) shows the need for appropriate intervention options over the planning horizon. Five intervention strategies are analysed in WaterMet^2 and their quantified performance is compared with respect to the criteria. Multi-criteria decision analysis is then used to rank the intervention strategies based on different weights from the involved stakeholders' perspectives. The results demonstrate that the best and robust strategies are those which improve the performance of both water supply and wastewater systems.

1 Introduction

One of the conventional approaches to model an urban water system (UWS) is to use a physically-based model to simulate the 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. This is demanding and tedious for many case studies. Additionally, 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, storm water and wastewater need to be considered together.

Some of the instances of these conceptually-based models that have been developed in the past are AQUACYCLE (Mitchell et al., 2001), UWOT (Makropoulos et al., 2008), UVQ (Mitchell and Diaper, 2010) and CWB (Mackay and Last, 2010). These models aim to simulate the integrated water system within an urban area and estimate the contaminant loads and the volume of the water flows throughout the UWS, from source to sink. Such a simulation enables the planners to explore a wide range of conventional and emerging

techniques in water supply, storm water and wastewater services to an UWS.

Despite a plethora of studies for modelling integrated urban water systems, they generally start with potable water from the points of water consumption. Therefore, potable water is modelled as an external supply and its demand is calculated as the sum of the neighbourhood demands 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 the water supply, sewerage and drainage subsystems. This is handled by means of a simplified and integrated approach for modelling water distribution and wastewater systems. Then, the physical metabolism of this integrated UWS is evaluated 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.

Furthermore, the focus of all of the previously-developed models is mainly based on the quantification of water-related flows and their final destinations in different parts of the UWS. However, the key performance indicators employed in this paper aim to quantify both water flows and other main fluxes of sustainability-related issues such as all types of direct and indirect (embodied) energy, material flows and greenhouse gas (GHG) emissions resulted from the activities in different elements of the UWS.

Further details of the developed model are briefly outlined below. The case study is elaborated upon subsequently. Results and discussions pertaining to the case study are presented thereafter. The paper closes with the conclusions and recommendations for further research. Note that this paper is an extension of the one presented at the 12th edition of the International Conference on "Computing and Control for the Water Industry – CCWI2013" (Behzadian et al., 2014b).

2 WaterMet^2 methodology

WaterMet^2 is a conceptual, simulation-type, mass-balance-based, integrated UWS model which quantifies the metabolism-related performance of a generic UWS with focus on sustainability related issues (Behzadian et al., 2014a). WaterMet^2 is also a standalone piece of software which runs in a Windows™ screen with the capability of navigational devices to build a new UWS model. It defines mains flows and storages of UWS through four main sub-systems including water supply, water demand, wastewater and cyclic water recovery (Behzadian and Kapelan, 2012).

WaterMet^2 recognises the entire urban water system as four spatial scales including indoor, local, subcatchment and city areas. The indoor areas represent the smallest spatial scale, and include single properties (e.g. residential, industrial, commercial, public, etc.) without any surroundings (e.g. gardens or public open outdoor spaces). Water demand profiles at this scale can be defined based on either the daily average of per-capita water demand or detailed information of the water consumption in the single properties. For the latter case, water demand can be further split into six types of appliances and fittings as (1) hand basin, (2) bath and shower, (3) kitchen sink, (4) dish-washer, (5) washing machine and (6) toilet. The Local area scale represents a group of similar typical households/properties with a surrounding area. It can contain any number of indoor areas (i.e. properties) but they all must be of the same type, i.e. with identical per-capita water demand. The surrounding area is divided into pervious and impervious surfaces. The main tasks of WaterMet^2 Local area are to handle outdoor water demands, rainfall-runoff modelling and on-site water treatment options. The subcatchment area scale represents a group of neighbouring local areas. The main tasks of WaterMet^2 Subcatchment area is to represent as (1) "water consumption points" of potable water in a simplified water supply system outlined below and (2) "collection points" of a storm water runoff and sanitary sewage in a simplified sewer system outlined below. A daily time-step and a user-defined period of N years are adopted as the time interval and duration of the model simulation in WaterMet^2. All this, in turn, will enable WaterMet^2 to model a wide range of elements in UWS from residential appliances, fittings and water recycling schemes to simplified water supply and sewer systems. Details of specifications and functional processes modelled at each scale can be found at the relevant references such as Behzadian et al. (2012).

The WaterMet^2 model adopts a simplified approach for the water supply subsystem in which "source to tap" modelling is performed. The elements modelled in the water supply subsystem which are shown in Fig. 1 are:

1. three key "storage" components including raw water resources, water treatment works (WTWs) and service reservoirs;
2. three principal flow "routes" including water supply conduits, trunk mains and distribution mains;
3. Subcatchments as water consumption points.

The simulation of the water supply subsystem is carried out in two steps in which water demand is calculated upwards in the first step and water is allocated downwards in the second step. More specifically, the first step deals with the calculation of the daily water demand starting from the most downstream points (i.e. subcatchments) and aggregating in the upstream direction until it reaches most upstream points (i.e. water resources). Through this step, the calculated water demand in the components may be limited by their capacity. The second step distributes water flow in the downstream direction starting from water resources. At the most upstream point, the water release (abstraction) from each water resource is supplied provided there is enough storage in

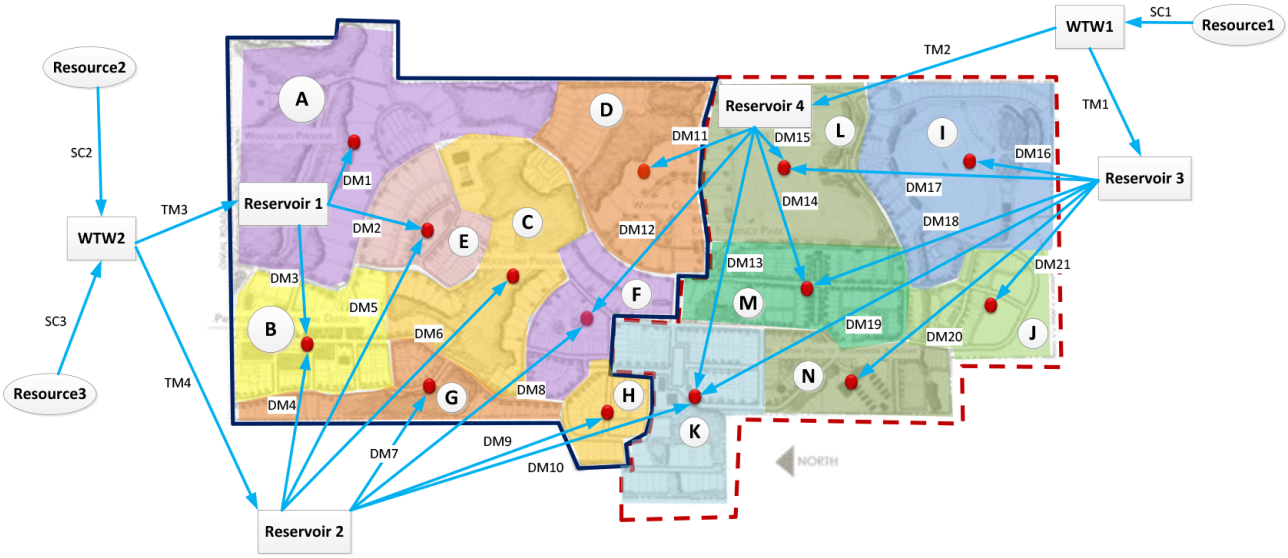

Figure 1. A schematic example of a water supply system representation in WaterMet^2; SC = water supply conduit; TM = trunk main; DM = distribution main; WTW = water treatment works.

the water resource. The water flow is allocated from multiple upstream components to multiple downstream components based on predefined allocation coefficients. The released/allocated water is transferred to the downstream elements subsequently until it reaches the Subcatchments in which water is distributed between the water demand points in the Local area(s).

Further, wastewater and storm water generated in the local areas of the Subcatchment are aggregated and represented as wastewater/storm water of the Subcatchment and start point in the simplified wastewater system represented in Fig. 2. This system comprises three key "storages":

1. Separate/combined sewer system interconnecting between Subcatchments themselves or between Subcatchment and wastewater treatment works (WWTWs);

2. WWTWs;

3. Receiving waters (only as "sink" points).

Storm water/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. More details of these simplified systems can be found in Behzadian et al. (2014a).

Each of the integrated UWS components used in WaterMet^2 (e.g. WTWs, trunk mains, etc.) is predefined in terms of its specific characteristics (e.g. WTWs capacity, trunk main flow capacity and specific energy used for conveying water, etc.). When a new WaterMet^2 model is being built, the required UWS components are selected and interlinked in a suitable configuration which represents the analysed UWS in the best way. A model simulation run is then performed by calculating the water flows in the UWS for a pre-specified duration and driven by the pre-specified system load (water demand and rainfall). This is done in a simplified way outlined above, based on the principles of mass balance (but by respecting relevant capacities and other characteristics of the modelled UWS components). As a result of this model simulation, principal flows/fluxes (e.g. energy, GHG emissions, chemicals and pollutants) are derived from the previously-estimated water flows by using suitable component characteristics (e.g. specific energy consumption for pumping). The detailed WaterMet^2 model outputs are then simply aggregated (spatially and/or temporally) to estimate the quantitative evaluation criteria values.

Furthermore, since WaterMet^2 is a conceptual, mass-balance-based model, it simply cannot model variations in pressure heads (such as hydraulic and physically-based models) and hence cannot calculate the results of such hydraulic simulations (such as pressure head or leakage variations). As a compromise, WaterMet^2 assumes the total leakage of the flow routes can be expressed as a percentage of water demand. This assumption can be considered as a reasonable approximation for the long-term, strategic level assessment of the UWS performance and was made by other similar models such as UVQ (Mitchell and Diaper, 2010), UWOT (Makropoulos et al., 2008) and CWB (Mackay and Last, 2010).

3 Case study

3.1 Introduction

The urban water system of the city of Oslo in Norway is used here as a reference city combined with assumptions when

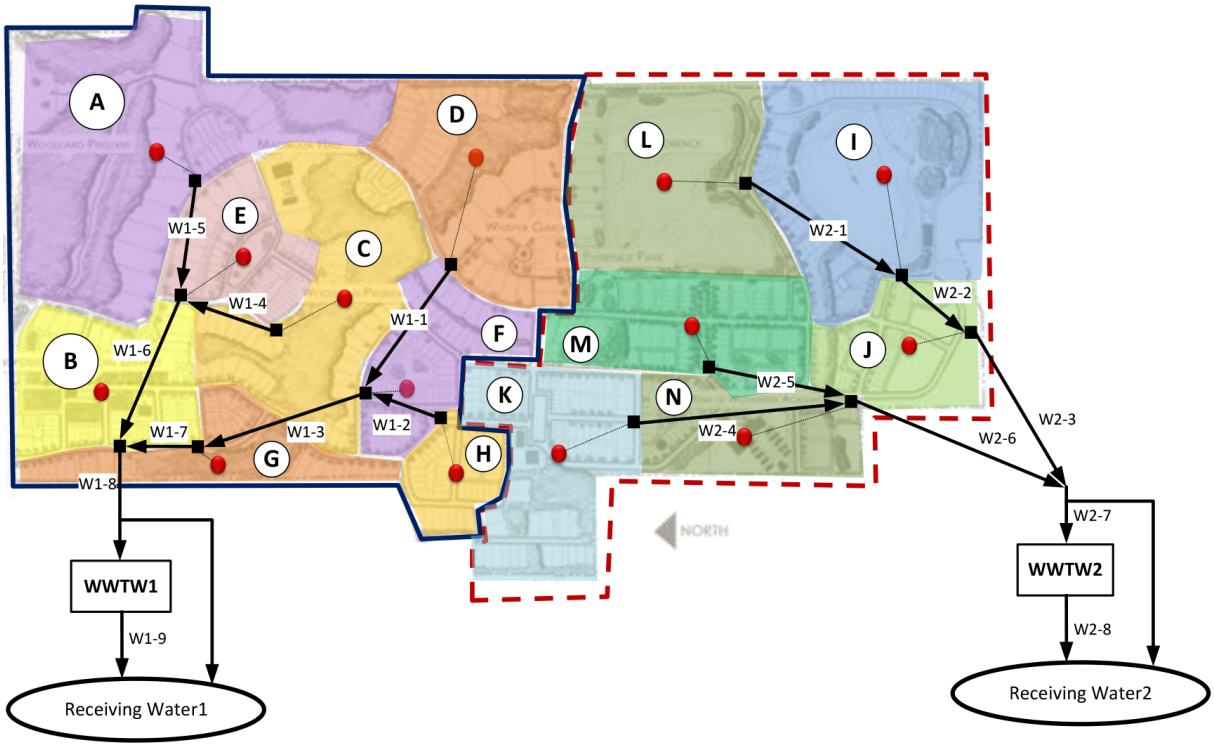

Figure 2. A schematic example of a sewer system representation in WaterMet^2; W1- & W2- = sewer system 1 and 2 respectively; WWTW = wastewater treatment works.

necessary. The existing Oslo UWS contains two main raw water resources each supplying to one of the two WTWs. The split between these raw water resources as far as freshwater supply is concerned is in the ratio 9 : 1 (VAV, 2011a). The UWS has a blend of combined and separate sewer systems and two WWTWs collecting 63 and 27 per cent of wastewater from the wastewater flow (VAV, 2006). The two water resources of the UWS are of limited capacity (60 and 13.8 million cubic metres – MCM) and inflow (287 and 12 MCM year^{-1}). 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 considered in this paper.

The WaterMet^2 model is demonstrated here through sustainability-based assessment of the integrated UWS over a 30 year planning horizon. The integrated UWS modelled by WaterMet^2 includes both the water supply and the wastewater systems as described above. WaterMet^2 quantifies the sustainability-based performance of both existing UWS and new intervention strategies which will be described in the following.

3.2 Building a (replicable) UWS WaterMet^2 model

UWS of the reference city (i.e. Oslo) is modelled using a single WaterMet^2 Subcatchment with a single Local area. The total number of properties in the city is 320 000 with a population of 610 000 in 2011. The highest rate of water demand as a consequence of the highest population growth projection is assumed for future water consumption in the UWS. Water demand of the local area is split into domestic, industrial, irrigation, frost tapping and unregistered public use (VAV, 2011b). Domestic (indoor) water demand per capita is assumed to be 180 L day^{-1}. The existing leakage from the pipelines is assumed to be 22 % of total water demand. The Oslo WaterMet^2 model was calibrated for the existing flow conditions in the UWS. The calibration was carried out using historical daily measurements of water production at WTWs and wastewater treated at WWTWs. The UWS model is first calibrated for water supply systems and then for wastewater systems using a manual, trial and error approach. For the first part, two years of recorded daily water production at WTWs split into two periods using 2011 for calibration and 2012 for validation. The calibration parameters for the WSS model include (1) monthly coefficients of water demand profiles; (2) percentage contribution of daily temperature in daily variation of water demand profiles. The wastewater system model is subsequently calibrated for two years (2010–2011) of recorded daily wastewater inflows to the WWTWs, again split into two one-year periods for calibration and validation. The relevant calibration parameters are hydrologic parameters of the Subcatchment and the principal hydraulic features of the WWTWs and sewer system. Further details of

the model and its calibration can be found in Behzadian and Kapelan (2012) and Behzadian et al. (2014a).

3.3 Intervention strategies

To improve the performance of the UWS – especially an increase in the reliability of water supply (will be shown in the results), some intervention strategies are suggested to be analysed using WaterMet^2 to find out how sustainability-based indicators are affected over the planning horizon. The following five intervention strategies are defined and evaluated for improvement of the performance of the UWS over a 30-year planning horizon (2011–2040):

Strategy#1: business-as-usual (BAU) strategy: as a benchmark strategy resembling "do nothing" over the planning horizon;

Strategy#2: addition of a new water resource: one new water resource and relevant WTWs are added from year-2020 to the UWS (it refers to option A2 out of the four options in the relevant report at VAV (2011a), Behzadian and Kapelan (2012).

Strategy#3: 1 % increase in annual pipeline rehabilitation rate: current annual rate of pipeline rehabilitation (i.e. 1 % of the total length of water supply pipelines) will be increased by 1 % from 2015 and the new rate will be 2 % over the rest of the planning horizon. Note that it is assumed that the current rate would cause the leakage percentage to remain constant but additional rate would proportionally decrease the leakage percentage (Venkatesh, 2012).

Strategy#4: 0.5 % increase in annual pipeline rehabilitation rate plus 10 % additional annual water meter installation: the new rate will be 1.5 % and water metering coverage of customers will annually increase 10 % of total domestic customers, both from 2015. Note that it is assumed that installing a new water meter would decrease a constant rate of 10 % for the water demand per capita (VAV, 2011b).

Strategy#5: addition of RWH and GWR systems at local level: single rainwater harvesting (RWH) and grey water recycling (GWR) systems representing all many small water treatment units across the city assuming that they are adopted by 50 % of households are added from 2015. It is assumed a tank capacity of 0.48 MCM and 39 000 m^3 for the represented RWH and GWR system, respectively (Ward et al., 2012a, b; Memon et al., 2005) which both provide water demands of toilet flushing, irrigation and industrial usages. 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., 2012a; Memon et al., 2005).

3.4 Evaluation criteria

The aforementioned intervention strategies are compared by using the following multiple evaluation criteria covering different dimensions of UWS sustainability (Alegre et al., 2012):

1. *Total capital costs:* the capital investments of the intervention options are discounted in year 2011 with 3 % discount rate.
2. *Total O&M costs:* both fixed (e.g. salary) and variable (e.g. electricity per cubic metre used) costs related to different components of the UWS over the planning horizon are discounted in year 2011 with 3 % discount rate.
3. *Reliability of water supply:* ratio between total water delivered to customers and total water demand over the planning horizon.
4. *Annual average of water leakage:* leakage volume in water distribution systems over the planning horizon relative to annual pipeline rehabilitation rate.
5. *Annual average of GHG emissions:* both types of direct GHG resulted from electricity and fossil fuel; and indirect GHG resulted from embodied energy over the planning horizon.
6. *Annual average of CSOs volume:* overflows from CSO structures from both combined sewer system and WWTWs over the planning horizon.
7. *Social acceptance:* as a qualitative sustainability indicator, it examines the extent of support that an intervention strategy receives from the society in order to fulfil the requirements of water services. In other words, this criterion reflects how much water users are willing to accept a strategy. This typically depends on a number of factors such as water quality and interruption to supply issues. This indicator is rated by expert opinion between 1 and 10 with 1 being the least acceptance and 10 the highest acceptance rate.

Note that the first six criteria values are calculated using the WaterMet^2 model whilst the last criterion value is estimated using the expert judgement. The quantitative criteria are selected such that the performance of all UWS components is included. More specifically, criteria 3 and 4 are related to the performance of the water supply system components while criterion 6 is dependent on the performance of the wastewater system components. The other quantitative criteria (i.e. 1, 2, 5) are dependent on the performance of all UWS components. Also, note that the aforementioned criteria values are likely to change when UWS system modifications are introduced by means of different interventions analysed (as these modify the UWS component characteristics).

3.5 Comparison of intervention strategies

To demonstrate the WaterMet^2 model capabilities for strategic planning of the UWS, the intervention strategies will be compared with respect to either a single criterion or multiple criteria. By single criterion comparisons with respect to each of the evaluation criteria separately, advantages and shortcomings associated with the application of the intervention strategies are envisaged. The multiple criteria comparison performed here by a Compromise Programming (CP) multi-criteria decision analysis (MCDA) technique provides a ranking for the intervention strategies. The CP method originally proposed by Zeleny (1973) calculates a distance function for each strategy that is nearest with respect to an "ideal" point for which all the criteria are optimized (André and Romero, 2008).

When ranking the strategies with respect to multiple criteria, weights can be assigned to each of the criteria to indicate the relative importance of those criteria. As these weights may be a key factor for some stakeholders, and may play a significant role in the final ranking, four various perspectives each representing a viewpoint of specific involved stakeholders in the UWS, are used to specify the weights. Then, the obtained rankings from various perspectives are finally combined to specify a single and final ranking. Four main stakeholders' perspectives are analysed here as: (1) equal weight (no biased view on criteria); (2) environmentalist; (3) water company; and (4) public. The weights of the evaluation criteria associated with these perspectives are given in Table 1.

4 Results and discussion

4.1 UWS performance using WaterMet^2

The business-as-usual (BAU) strategy is first analysed in WaterMet^2 for a daily time-step over a 30-year planning horizon. Figure 3 shows the WaterMet^2 simulation for the monthly water demand and percentage of the delivered water demand in the city for 'do nothing' strategy over the planning horizon. As it can be seen, the UWS in this strategy is unable to fully supply the increasing potable water demand due to the population growth. The monthly water deficit starting slightly in the beginning years will expand rapidly over the following years with a great magnitude (less than 75 % of monthly water demand delivered in the last years as shown in Fig. 3). Thus, the water supply reliability calculated by WaterMet^2 is 94 % for the BAU (Table 2).

Figure 4 shows the contribution of three main components towards annual average of per-capita GHG emission for the BAU. WWTWs contributes the most to the total per-capita GHG emissions (91 kg CO_2-eq) owing to the considerable share of embodied energy in the chemicals used for wastewater treatment in WWTWs. This implies that intervention options aimed at decreasing the inflow of wastewater to WWTWs can be highly effective in decreasing GHG

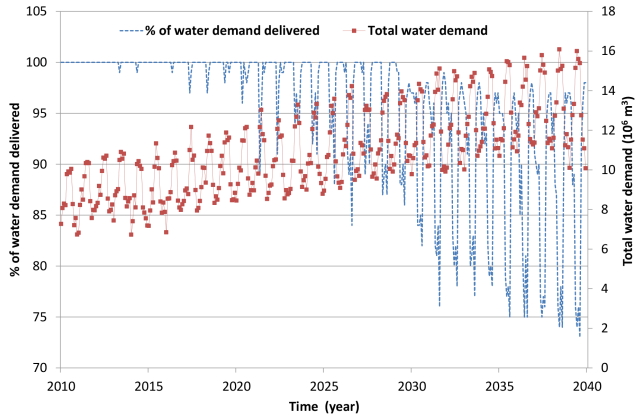

Figure 3. Water demand projection and monthly percentage of water demand delivered over the planning horizon for the BAU.

emissions. In addition, although fossil fuel is basically categorised as a source of high GHG emissions per unit volume consumption, its share here as shown in Fig. 4 is the least among all components of the UWS because of relatively negligible consumption in the UWS components (e.g. 0.002 and 0.004 L m^{-3} in WTWs and distribution systems, respectively).

The evaluation of the five intervention strategies calculated by the WaterMet^2 model is shown in Table 2. Each new intervention strategy relative to the BAU can gain some noticeable enhancement with respect to each of the criteria. In particular, the water supply reliability increases from 94 % in the BAU to at least 96 % in Strategy 3 and 100 % when new water sources are added (Strategy 2). However, an increase in reliability of water supply is achieved at a cost – huge capital investment required for building new water resources and associated WTWs in Strategy 2 or less expensive strategies (#3–5).

Strategy 5 has the highest O&M cost compared to other strategies although this strategy reduces both clean water demand and wastewater generated, and thus is expected to decrease energy cost in all relevant components. This increase can be linked to the fact that the fixed and operational costs of both RWH and GWR systems defined in Strategy 5 are far more than the reduction in O&M expenses in other UWS components. Strategy 2 is the second most-expensive O&M expenditure which is far beyond that of the BAU strategy. This is due to the provision of more clean water in water supply, and the concomitant increase in expenditure on energy in WTWs and distribution systems. New strategies 3 and 4 have a relatively negligible priority compared to the BAU with respect to O&M expenses (Table 2 and Fig. 5). This can be attributed to the fact that the reduction in O&M expenses, owing to less clean water demand (as a result of leakage reduction and water consumption) and less wastewater generation (Strategy 4), is slightly more than the increase in expenses incurred by pipeline rehabilitation.

Table 1. Weights of the criteria from different perspectives.

Criteria	Capital cost	O&M Cost	Reliability	Leakage	GHG emissions	CSOs volume	Social acceptance
Perspective							
Equal weight	1	1	1	1	1	1	1
Public	0.33	0.33	0.67	0.33	0.33	0.33	1
Environmentalist	0.5	0.5	0.5	0.5	1	1	0.5
Water company	0.2	0.2	1	0.2	0.2	0.33	0.67

Table 2. Evaluation of intervention strategies.

Criteria	Capital cost	O&M Cost	Reliability of supply	Leakage	GHG emissions	CSO volume	Social acceptance
Units	Million Euro	Million Euro year^{-1}	%	MCM year^{-1}	10^3 t year^{-1}	MCM year^{-1}	–
Objective type	Min	Min	Max	Min	Min	Min	Max
Strategy #1 (business as usual)	0	43.1	94	23	95	306	5
Strategy #2 (additional water source)	389	49.4	100	25	98	311	7
Strategy #3 (1% additional annual rehabilitation)	132	43.0	96	19	96	307	6
Strategy #4 (0.5% additional annual rehabilitation & 10 % additional annual water meter installation)	63	42.9	97	21	93	298	5
Strategy #5 (RWH and GWR systems)	270	51.0	99	19	89	209	3

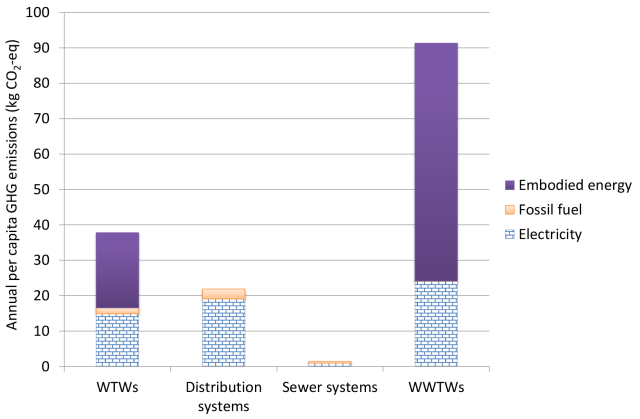

Figure 4. Contribution of three sources of GHG emissions towards annual average of per capita GHG emission in the main UWS components for the BAU.

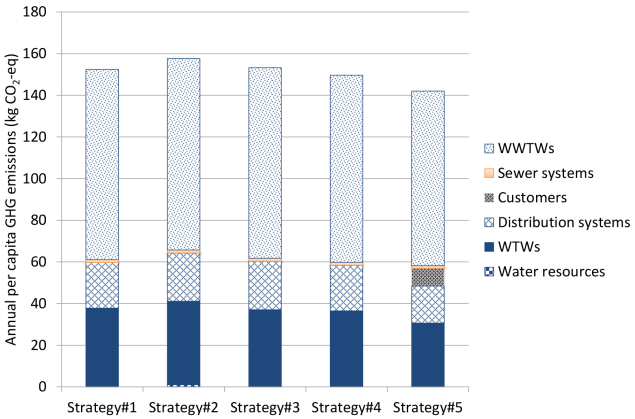

Figure 5. Annual average of per capita GHG emission for intervention strategies.

The performance of the existing UWS with respect to leakage can be improved substantially over the planning horizon by Strategies 3–5 (Table 2). This improvement can be either directly due to additional annual rehabilitation (Strategies 3–4) or indirectly due to GWR and RWH systems (Strategy 5) by reducing potable water consumption. On the other hand, Strategy 2 has more leakage than the BAU since Strategy 2 provides more potable water in the UWS and the leakage as a constant percentage of water supplied increases.

Figure 5 represents the annual average of GHG emissions in the UWS and its components for five intervention strategies. Strategy 5 compared to other strategies generates the minimum amount of annual average of per-capita GHG (142 kg CO_2-eq) although only this strategy generates GHG in the customers component due to the use of Local water recycling schemes. This can also be attributed to fact that this strategy in favour of water recycling schemes cuts down the amount of both potable water demand and wastewater generation. The overall reduction in the annual average of per-capita GHG emissions for this strategy compared to the BAU

is 18.8 kg CO_2-eq including 7.18, 4.16 and 7.47 kg CO_2-eq for WTWs, distribution systems and WWTWs respectively. However, this strategy causes GHG emissions of households (end-users) to increase as much as 8.54 kg CO_2-eq per capita. On the other hand, Strategy 2 generates more GHGs than the BAU because of more potable water supplied in this strategy would cause more energy required for both water supply and wastewater sub-systems.. A thorough comparison of the annual averages of per-capita GHG emissions in Strategy 3 with those in the BAU reveals that less potable water demand as a consequence of leakage reduction can cause a negligible reduction of GHG emissions in WTWs (0.71 kg CO_2-eq) while increasing the same by 1.36 and 0.82 kg CO_2-eq for additional pipeline rehabilitation and 2 % increased wastewater generation, respectively. Thus, Strategy 3 generates slightly greater GHG emissions than the BAU (Table 2). However, Strategy 4 amends the intervention option of Strategy 3 by decreasing the magnitude of pipeline rehabilitation plus water demand consumption. Hence, Strategy 4 reduces the annual average of per-capita GHG emissions in WTWs and WWTWs by 1.30 and 1.47 kg CO_2-eq, respectively, while offsetting the emissions in distribution systems. This would lead this Strategy to generate slightly less GHG emissions than the BAU.

The performance of the UWS with respect to the "CSO volume" criterion for different strategies is influenced by generated runoff and sanitary sewage of customers in sewer systems (Table 1). More specifically, Strategy 5 with the lowest level of CSO discharge causes the overflow volume in sewer systems to significantly reduce (by 32 %). This can be attributed to both reduced runoff entering the combined sewer system courtesy runoff-collection by the RWH systems, and reduced wastewater generated owing to the fact that GWR systems reuse grey water for specific indoor and outdoor consumptions. The second lowest CSO discharge which is slightly less than the BAU is related to Strategy 4 as it can only mitigate wastewater generated by reducing water consumption as a result of water meter introduction. Strategies 2 and 3 both cause more wastewater to be generated as a result of providing more clean water supply, and thus the CSO volume increases slightly. It is also noted that although Strategy 3 can cause 17 % reduction in leakage amount and subsequently augment reliability by 2 %, it would increase the wastewater generated and subsequently magnify the CSO volume, thanks to a 2 % increase in potable water supply.

Table 2 also presents a qualitative assessment (social acceptance) of the UWS for intervention strategies quantified by expert judgement. Strategy 2 is the most socially-acceptable, as it can fulfil the requirements of the customers, in a better way. Strategies which include rehabilitation (#3 and #4) follow Strategy 2, as far as social acceptance is concerned, as in both these cases, both the incidence of breaks and the quantity of leakage is likely to be reduced.

4.2 Ranking of intervention strategies

Further analysis is carried out by ranking the intervention strategies based on both single criterion and multiple criteria approaches. Figure 6 shows the single criterion ranking of the strategies with respect to each of the seven evaluation criteria. Whereas Strategy 2 compared to other strategies is ranked number one relative to water supply reliability and "social acceptance", it is ranked the worst (fifth strategy) with respect to four criteria (i.e. capital cost, leakage, GHG emissions and CSO volume). For three criteria (i.e. leakage, GHG emissions and CSO volume) out of the four in which Strategy 2 is ranked the lowest, Strategy 5 is the highest while it is ranked the lowest relative to two criteria (i.e. O&M cost and social acceptance).

Table 3 shows the ranking of the intervention strategies based on multiple criteria. In this Table, the CP method calculates four rankings related to the four different perspectives based on the criteria weights specified in Table 1. It can be seen from Table 3 that the ranking from "environmentalist's" perspective is almost similar to those of "equal weight's" although environmentalist has a bias towards the environmental criteria (i.e. GHG and CSO). This can be due to the high influence of these strategies by the environmental criteria in "equal weighting" perspective. In addition, the close similarity of rankings between "public's" and "water company's" perspectives stem from the fact that their main concern over the UWS is more similar to each other, compared to other perspectives. More specifically, the best and the worst strategies for these two perspectives are Strategies 2 and 1, respectively, while Strategy 2 is ranked the worst from "equal weight's" and "environmentalist's" perspectives.

To incorporate these four rankings obtained from different perspectives into one final ranking, the sum of the ranks for each intervention strategy is used to calculate final ranking which is shown in the right-hand most column of Table 3. The following can be inferred from the comparison of the rankings:

1. The highest ranked strategies are complex ones (#4–5) containing two individual intervention options.

2. The ranks of these two strategies (4 & 5) and Strategy 1 are the most robust ones due to the fact that they are almost in the top and bottom strategies, respectively, from different perspectives.

3. On the other hand, Strategy 2 has the least robustness owing to the major changes of its rank in different rankings. Due to this reason, this strategy is finally ranked relatively low although it is ranked high from two perspectives.

Finally, note that the above analysis and the relevant rankings shown here should be used for illustrative purposes only in order to represent the type of the post-analysis which can done by using the WaterMet^2 model. Further analysis is

Table 3. Ranking based on the CP method.

Criteria Strategy	Equal weight	Public	Environmentalist	Water company	Sum of rankings	Final rank
Strategy #1 (business as usual)	4	5	4	5	18	5
Strategy #2 (additional water source)	5	1	5	1	12	3
Strategy #3 (1 % additional annual rehabilitation)	3	2	3	4	12	3
Strategy #4 (0.5 % additional annual rehabilitation & 10 % additional annual water meter installation)	1	3	2	3	9	1
Strategy #5 (RWH and GWR systems)	2	4	1	2	9	1

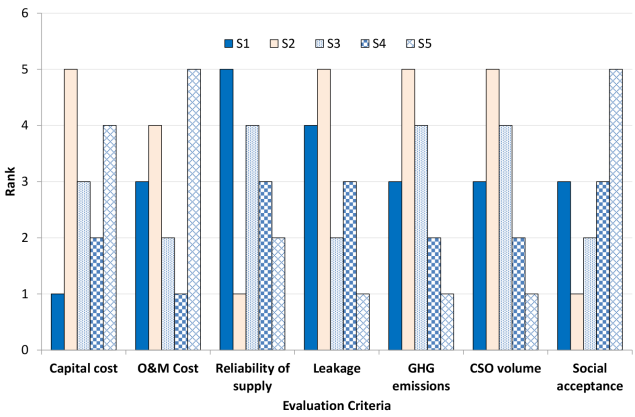

Figure 6. Ranking of the five intervention strategies (S1–S5) with respect to each of the evaluation criteria

needed to consider different scenarios and risk-based criteria in order to achieve a robust solution in the UWS.

5 Summary and conclusions

The new WaterMet^2 model was demonstrated here for strategic planning of the real-life UWS facing a problem of supply/demand balance in the future. The long-term analysis of the existing UWS by WaterMet^2 revealed the potential shortcomings especially water supply reliability. To tackle this problem, WaterMet^2 calculates the performance indicators of the UWS for five potential intervention strategies. They were then compared with respect to each of the six quantitative criteria calculated by WaterMet^2 and one qualitative criterion rated by expert's opinions. For strategic planning of the UWS, the CP method was finally used to rank the intervention strategies analysed by the WaterMet^2 model.

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. More specifically, WaterMet^2 quantifies both water-related and metabolism-related performance which can define sustainability type indicators such as GHG emissions in UWS components. To overcome the difficulties in UWS, WaterMet^2 enables the planners to track down the detailed impact of the performance of new intervention strategies on the UWS components. WaterMet^2 as an integrated modelling tool in UWS also enables the planners to analyse the long-term impact of intervention options on both water supply and wastewater systems simultaneously. Furthermore, the complex strategies with the aim of improving the performance of both water supply and wastewater systems were ranked the highest. The rankings of these complex strategies and the BAU are reasonably robust from the perspectives of all parties due to the similar criteria prioritization.

Although the results shown here indicate some promising strategies, to obtain a real-life solution, a wide range of different intervention strategies needs to be defined and further tested and evaluated by the WaterMet^2 model for multiple future scenarios and risk type criteria. Note that the analysis conducted and the corresponding results obtained in this paper do not reflect the views of the Oslo VAV and have been used only to demonstrate possible application and functionality of the WaterMet^2 simulation model and software tool.

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