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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 new "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, greenhouse gas emissions. The suggested model is demonstrated through sustainability-based assessment of an integrated UWS of Oslo city for daily time step over a 30 yr planning horizon. The integrated UWS modelled by WaterMet^2 includes both water supply and wastewater systems. Given a fast 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 are 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 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 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 CWB (Mackay and Last, 2010). These conceptual 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 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 emissions resulted from the activities in different elements of the UWS.

Further details of the developed model are briefly outlined below. The rest of the paper is continued by explaining the case study. Then, the results and discussion are presented. Finally, the conclusions are drawn and some recommendations are made.

2 WaterMet^2 methodology

WaterMet^2 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). 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 subsystems including water supply, water demand, wastewater and cyclic water recovery (Behzadian et al., 2012b). Principal flows quantified by WaterMet^2 in the UWS components are all types of water flow (Makropoulos et al., 2008), flux of energy (i.e. electricity, fossil fuel, embodied energy), greenhouse gas emission (GHG), chemical and pollutant.

WaterMet^2 recognises whole urban water system as four spatial scales including indoor, Local, Subcatchment and city areas. A daily time step and a user defined period of N years are adopted as time interval and duration of model simulation in WaterMet^2. All this, in turn, will enable WaterMet^2 to model broad range of elements in UWS from residential appliances and fittings and water recycling schemes to simplified water supply and sewer systems. More detail of specifications and functional processes modelled at each scale can be found at the relevant references such as Behzadian et al. (2013).

The infrastructure and performance of a typical urban water supply system (WSS) is followed in WaterMet^2 by modelling a simplified WSS shown in Fig. 1. It comprises four types of key “storage” nodes interconnected by three types of water flow “routes”. The key 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 net-

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work mains 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. 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 represented in Fig. 2. 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. More details of these simplified systems can be found in Behzadian et al. (2012a).

3 Case study

3.1 Problem description

The urban water system of Oslo city in Norway is used here for demonstration of the WaterMet^2 model. Existing Oslo UWS contains two main raw water resources each with the corresponding WTWs which 90 and 10 % of total fresh water (VAV, 2011a). The Oslo UWS has a mix of combined and separate sewer system and two WWTWs collecting 63 and 27 per cent of wastewater from the wastewater flow (VAV, 2006). The two water resources of Oslo UWS are of limited capacity (60 and 13.8 million cubic metres (MCM)) and inflow (287 and 12 MCM yr^{-1}). The daily time series of the last 30 yr inflows (1981–2010) into these water resources are selected and assumed to be the time series of inflow over the next 30 yr planning horizon.

The WaterMet^2 model is demonstrated here through sustainability-based assessment of the integrated Oslo UWS over a 30 yr 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 Oslo WaterMet^2 model

Oslo UWS is modelled using a single WaterMet^2 Subcatchment with a single local area. The total number of properties in Oslo 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 Oslo UWS. The calibration was carried out based on historical daily measurements of water production at WTWs and wastewater treated at WWTWs. Further details of the model and its calibration can be found in Behzadian and Kapelan (2012) and Behzadian et al. (2013).

3.3 Intervention strategies

To improve the performance of the Oslo UWS especially increase in the water supply reliability (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 Oslo UWS over a 30 yr 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 2020 to the Oslo UWS (it refers to option A2 out of the four options in the relevant report at Oslo 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's 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.

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 single criterion or multiple criteria. By single criterion comparisons with respect to each of the evaluation criteria separately, advantages and shortcomings associated with application of the intervention strategies are envisaged. The multiple criteria comparison performed here by a Compromise Programming (CP) multi-criteria decision analysis (MCDA) technique provide 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" points 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. The stakeholders constitute these four perspectives are (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 BAU strategy is first analysed in WaterMet^2 for daily time step over a period of 30 yr planning horizon. Figure 3 shows the WaterMet^2 simulation for the monthly water demand and percentage of the delivered water demand in the Oslo 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 GHG emission per capita for the BAU. WWTWs makes up the greatest contributor in total GHG emission per capita (91 kg CO_2-eq) owning to the considerable share embodied energy as a result of chemicals for wastewater treatment in WWTWs. This implies that intervention options aimed at decreasing wastewater inflow to WWTWs can be highly effective in decreasing GHG 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 adding new water sources (Strategy 2). However, increased reliability of water supply is achieved at the cost of large 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 saved O&M cost in other UWS components. Strategy 2 is the second most expensive O&M cost which is far beyond that of the BAU strategy. This is due to providing more clean water in water supply and thus increasing energy costs of in WTWs and distribution systems. New strategies 3 and 4 have a relatively negligible priority compared to the BAU with respect to O&M cost (Table 2 and Fig. 5). This can be attributed to the fact that saving O&M cost, 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 increased O&M costs incurred by pipeline rehabilitation.

The performance of the existing Oslo UWS with respect to leakage can be improved substantively 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 Oslo UWS and its components for five intervention strategies. Strategy 5 compared to other strategies generate the minimum amount of annual average of GHG per capita (142 kg CO_2-eq), although only this strategy generates GHG in the customers component due to the using of water recycling schemes, it. This can also be attributed to fact that this strategy in the favour of water recycling schemes cuts down the amount of both potable water demand and wastewater generation. The overall reduction in the annual average

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of GHG emissions per capita 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 while increasing 8.54 kg CO_2-eq per capita in the customers component. On the other hand, Strategy 2 generates more GHG than the BAU because of more potable water supplied in this strategy would cause more energy required for both water supply and wastewater components. Detailed comparison of annual average GHG emissions per capita in Strategy 3 with those in the BAU reveals that less potable water demand as a consequent of leakage reduction can cause a negligible reduction of GHG emissions in WTWs (0.71 kg CO_2-eq) while increasing 1.36 and 0.82 kg CO_2-eq for additional pipeline rehabilitation and 2 % increased wastewater generation, respectively. Thus, Strategy 3 generates a slightly more 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 GHG emissions per capita 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 a slightly less GHG emissions than the BAU.

The performance of the UWS with respect to "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 (32 %). This can be attributed to both reduced runoff entering the combined sewer system as a result of collecting runoff by RWH systems and reduced wastewater generated in the favour of GWR systems reusing 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 CSO volume increases slightly. It is also noted that although Strategy 3 can alleviate 17 % leakage amount and subsequently augment reliability by 2 %, it would increase the wastewater generated and subsequently magnify the CSO volume as a result of 2 % increase in potable water supply.

Table 2 also presents a qualitative assessment (social acceptance) of the UWS for intervention strategies quantified by expert's judgement. Strategy 2 is the most acceptable by the society as it can better fulfil the requirements of the customers. The next most highly-regarded strategies with respect to this criterion are those containing rehabilitation (i.e. Strategies 3 and 4) as in these cases, both the incidence of breaks and the quantity of leakage is likely to be reduced and thus customer satisfaction is more provided.

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 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 can be originated from the fact that their main concern over the UWS is partly closed to each other compared to others. 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 and 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. Rather, further analysis is 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 Oslo 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 ranks of these strategies and the BAU are the most robust ones from different perspectives due to being influenced by all the criteria uniformly.

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.

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References

Alegre, H., Cabrera Jr., E., Hein, A., and Brattebø, H.: Framework for sustainability assessment of UWCS and development of a self-assessment tool, TRUST report, 2012.

André, F. J. and Romero, C.: Computing compromise solutions: on the connections between compromise programming and composite programming, Appl. Math. Comput., 195, 1–10, doi:10.1016/j.amc.2007.04.064, 2008.

Behzadian, K. and Kapelan, Z.: Oslo Case Study Report, University of Exeter, Exeter, UK, 2012.

Behzadian, K., Kapelan, Z., Rozos, E., and Makropoulos, C.: WaterMet^2 Model Functional Requirements, University of Exeter, NTUA, 2012a.

Behzadian, K., Kapelan, Z., Rozos, E., and Makropoulos, C.: WaterMet^2 Conceptual Model, University of Exeter, NTUA, 2012b.

Behzadian, K., Kapelan, Z., Venkatesh, G., Brattebø, H., Sægrov, S., Rozos, E., Makropoulos, C., Ugarelli, R., Milina, J., and Hem, L.: Urban water system metabolism assessment using WaterMet^2 model, 12th International Conference on Computing and Control for the Water Industry, CCWI2013, Perugia, Italy, 2013.

Mackay, R. and Last, E.: SWITCH city water balance: a scoping model for integrated urban water management, Reviews in Environmental Science and Bio/Technology, 9, 291–296, doi:10.1007/s11157-010-9225-4, 2010.

Memon, F. A., Butler, D., Han, W., Liu, S., Makropoulos, C., Avery, L. M., and Pidou, M.: Economic assessment tool for greywater recycling systems, Proceedings of the ICE-Engineering Sustainability, 158, 155–161, 2005.

Mitchell, V. G. and Diaper, C.: UVQ User Manual: (Urban Water Balance and Contaminant Balance Analysis Tool), CSIRO, 2010.

Mitchell, V. G., Mein, R. G., and McMahon, T. A.: Modelling the urban water cycle, Environ. Modell. Softw., 16, 615–629, 2001.

VAV: Water Supply Sewerage and Environment Customer Services Finances and Rates Organisation, Oslo Water and Sewerage Works, Oslo, Norway, 2006.

VAV: “Rough Analysis of Alternatives” translated from the original Norwegian version to English by: Venkatesh, G., Oslo Water and Sewerage Works, Oslo, Norway, 2011a.

VAV: “Forecast of Water Usage in the Future in Oslo” translated from the original Norwegian version to English by: Venkatesh, G., Oslo Water and Sewerage Works, Oslo, Norway, 2011b.

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

Ward, S., Butler, D., and Memon, F. A.: Benchmarking energy consumption and CO_2 emissions from rainwater-harvesting systems: an improved method by proxy, Water Environ. J., 26, 184–190, doi:10.1111/j.1747-6593.2011.00279.x, 2012a.

Ward, S., Memon, F. A., and Butler, D.: Performance of a large building rainwater harvesting system, Water Res., 46, 5127–5134, doi:10.1016/j.watres.2012.06.043, 2012b.

Zeleny, M.: Compromise programming, in: Multiple Criteria Decision Making, University of South Carolina Press, Columbia, South Carolina, 1973.

Table 1. Weights of the criteria from different perspectives.

Criteria Perspective	Capital cost	O&M Cost	Reliability	Leakage	GHG emissions	CSOs volume	Social acceptance
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 Units Objective type	Capital cost Million Euro Min	O&M Cost Million Euro yr^{-1} Min	Reliability of supply % Max	Leakage MCM yr^{-1} Min	GHG emissions $10^3 t yr^{-1}$ Min	CSO volume MCM yr^{-1} Min	Social acceptance – 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 and 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

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 and 10 % additional annual water meter installation)	1	3	2	3	9	1
Strategy #5 (RWH and GWR systems)	2	4	1	2	9	1

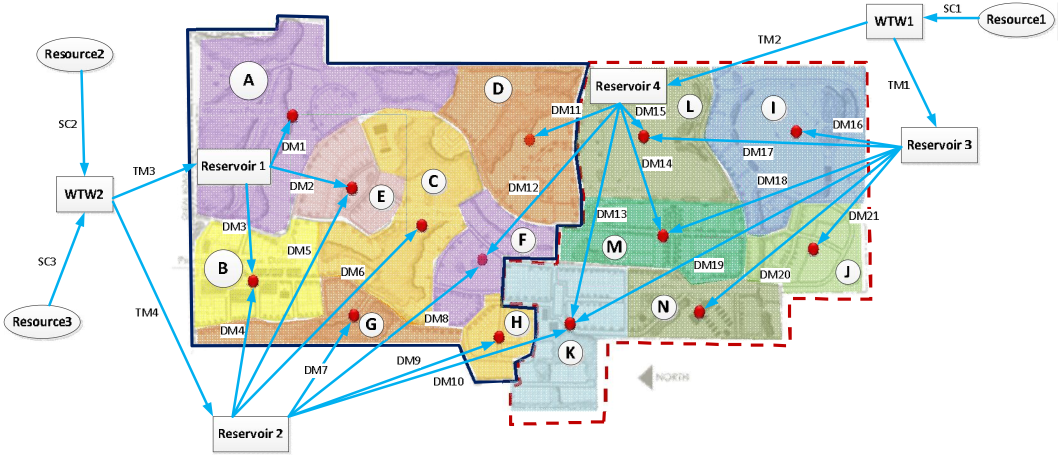

Fig. 1. A schematic example of a water supply system representation in WaterMet^2; SC = water supply conduit; TM = trunk main; DM = distribution main.

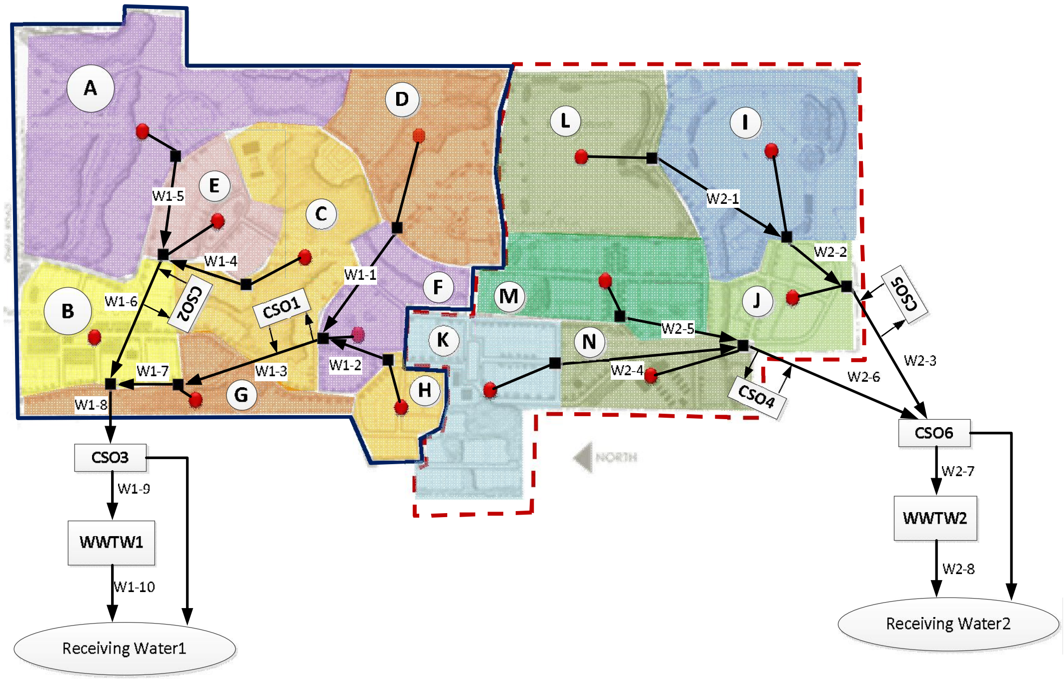

Fig. 2. A schematic example of a sewer system representation in WaterMet^2.

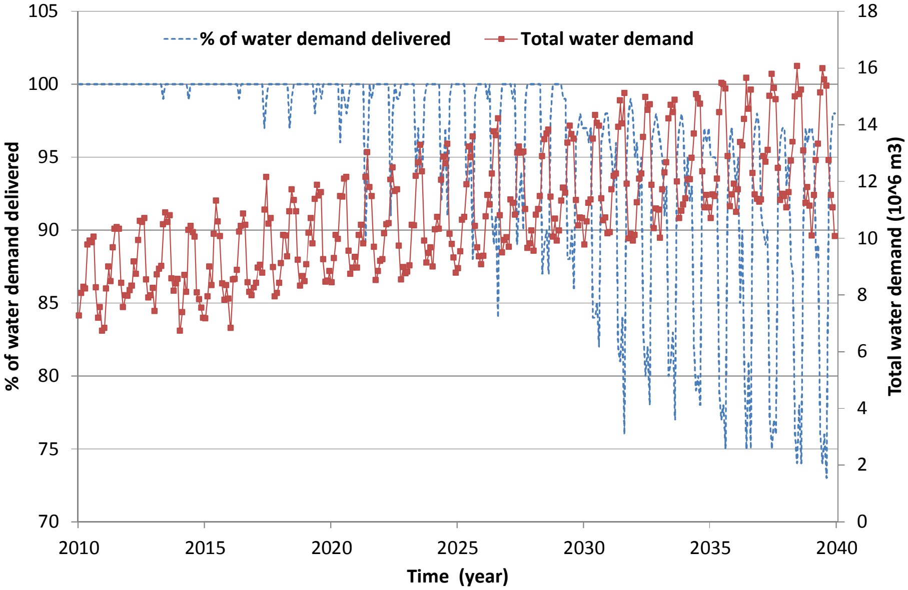

Fig. 3. Water demand projection and monthly percentage of water demand delivered over the planning horizon for the BAU.

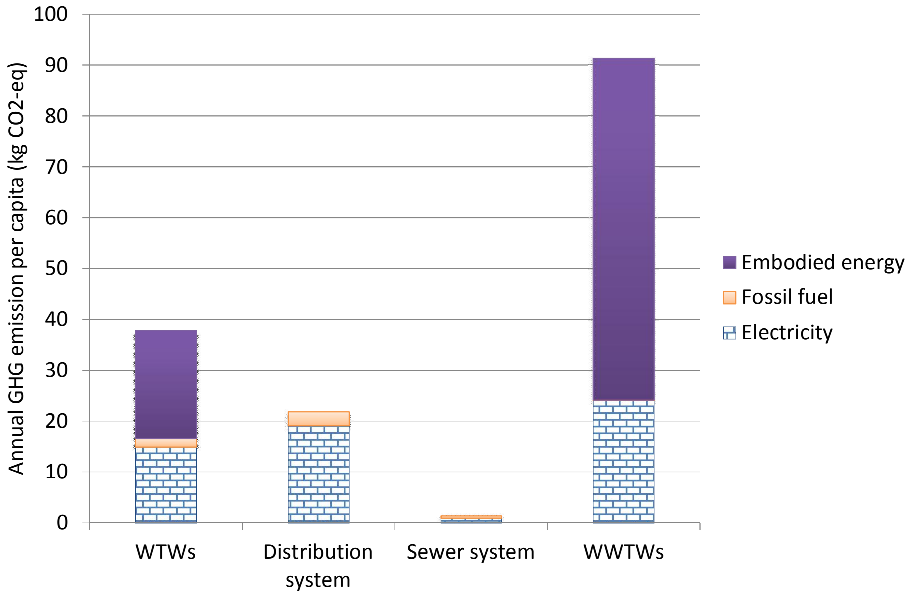

Fig. 4. Contribution of three sources of GHG emissions towards annual average GHG emission per capita in the main UWS components for the BAU.

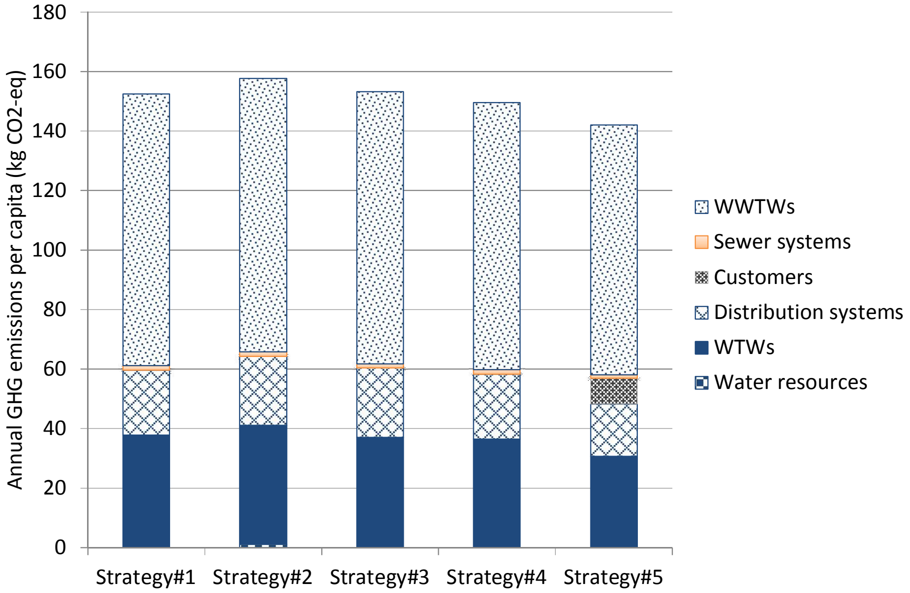

Fig. 5. Annual GHG emission per capita for intervention strategies.

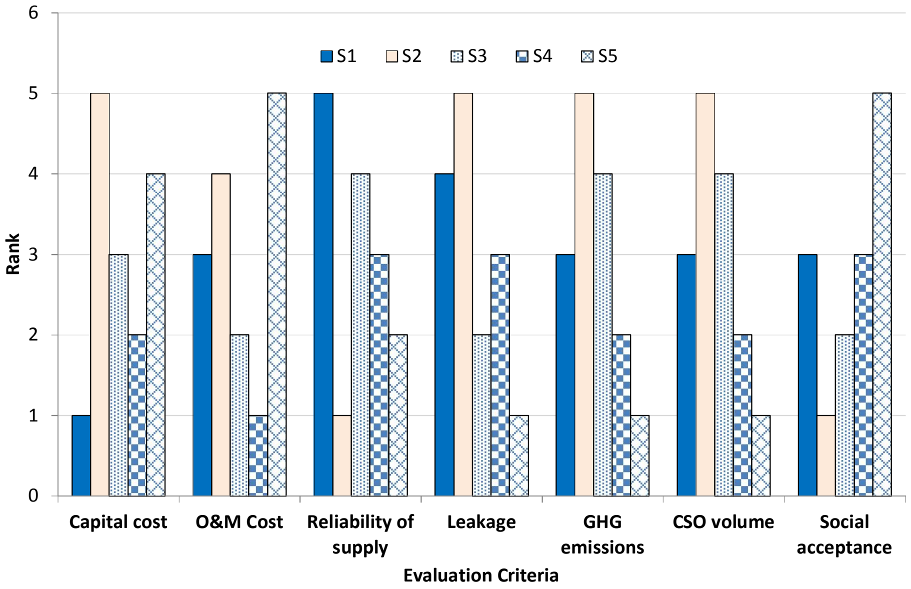

Fig. 6. Ranking of the five intervention strategies (S1–S5) with respect to each of the evaluation criteria.