# Modelling Metabolism Based Performance of an Urban Water System using WaterMet$^2$

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## Abstract

This paper presents a new quantitative model called ‘WaterMet$^2$’ for the *metabolism* based assessment of the integrated urban water system (UWS) performance. WaterMet$^2$ quantifies a number of UWS flows/fluxes (e.g. water and energy) which can be used to derive sustainability-based performance metrics. The generic WaterMet$^2$ model overcomes the drawbacks of the existing UWS models and strives to bridge the gaps related to the nexus of water, energy and other environmental impacts in an integrated UWS. The main features of WaterMet$^2$ are: (1) conceptual simulation model of UWS comprised of water supply, stormwater and wastewater subsystems with possible centralised and decentralised water reuse; (2) UWS represented by an arbitrary number of key UWS components for each type in four spatial scales (System, Subcatchment, Local and Indoor areas) in a distributed modelling type approach; (3) quantifying the metabolism-based performance of UWS including the caused and avoided environmental impact categories (GHG emissions, acidification and eutrophication potentials) and resource recovery in UWS. WaterMet$^2$ is tested, validated and demonstrated by evaluating the long-term performance of the UWS of a northern European city for three states including business as usual and two intervention strategies: addition of new water resources and large scale localised water recycling. The results obtained demonstrate the effectiveness of WaterMet$^2$ in evaluating the sustainability related UWS performance, the suitability of using WaterMet$^2$ at the strategic level UWS planning and the importance of using an integrated assessment approach covering the full urban water cycle.

*Keywords:* Urban water system; WaterMet$^2$; metabolism; performance; environmental impact categories;

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## 1. Introduction

Increasing urban water demands due to population growth is becoming a concern for many water companies (Nair *et al.,* 2014). This is already a major challenge in arid and semi-arid regions where climate change intensifies water scarcity through severe droughts given limited water resources available (Field *et al.,* 2014). On the other hand, climate change and urbanisation are the primary causes of increased urban

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flood in many humid regions (Savic *et al.*, 2013). All this in addition to the overall demand for good water quality in urban areas in the future (UNESCO 2012) imposes considerable stress on water companies to achieve technically and economically acceptable levels of service in the urban water system (UWS). Given ageing infrastructure, retrofitting of UWS is high on the agenda which needs intensive energy demands and subsequently cause a lot of environmental impacts. While achieving the satisfactory levels of services for UWS may be possible through enormous capital investment, meeting certain levels of sustainability criteria must be ensured (Behzadian *et al.*, 2014a). Such a strategy for new interventions in the UWS should consider not only the environmental impacts of the existing UWS operations but also those impacts due to the introduction of new interventions in the future.

This aim can be realised within an integrated framework of UWS in which the impact of the interactions between components can be measured concurrently on the whole systems. This approach can form a conceptually based model in UWS with the ability of quantifying metabolism fluxes (Venkatesh and Brattebø, 2011). Such a model is expected to identify the sustainability performance of UWS by using suitable indicators given the growing need for a holistic and sustainable management approach. Modelling the urban water cycle has been of interest for many decades (Rozos *et al.*, 2010). A surge in interest is seen after the mid-1990s and, thereafter, the scope has been widened and the number and types of aspects included in the models have further increased. Several tools have been developed in the recent decades to analyse the sustainability and cost effectiveness of the UWS. Different dimensions of the sustainability framework in water systems, i.e. economic, environmental, social, asset and governance (Alegre *et al.*, 2012), have been addressed by these tools. Recently developed tools are *Aquacycle* as a water balance model (Mitchell *et al.*, 2001), *UWOT* as a sustainable water management tool for selection of combinations of water-saving technologies (Makropoulos *et al.*, 2008), *UVQ* as a further modified *Aquacycle* to include contaminant and energy flow (Mitchell and Diaper 2006; Mitchell and Diaper, 2010) and *CWB* as city water balance model (Mackay and Last, 2010), a dynamic model developed by Fagan *et al.* (2010) and *DMM* as a dynamic metabolism model (Venkatesh *et al.*, 2014) to name but a few. A number of commercial integrated water cycle management tools have also been developed in recent years by eWater organisation in Australia such as *MUSIC* as an effective urban stormwater model for assessment of water sensitive urban design, *Urban Developer* as decision-support tool for integrated urban water management and *eWater Source* as a flexible enterprise modelling platform for urban water supply management (eWater 2014). The agent based approach has also been used by some models to represent autonomous social behaviours of stakeholders in the sustainability domain of water management (e.g. Valkering *et al.*, 2009).

Water, energy and environmental impact categories in UWS are linked through multiple interactive pathways. Essentially, the depth and intensity of those linkages can vary enormously in different UWSs among countries and regions with specific system components (Field *et al.*, 2014). A desirable UWS model should be able to quantify these impacts within a comprehensive framework. Despite a plethora of studies related to the assessment of alternative water management options, a comprehensive literature review by Nair *et al.* (2014) revealed that there is a major gap related to lack of a holistic framework to capture the dynamics of multiple water-energy-greenhouse gas (GHG) linkages in the UWS modelling. A comprehensive assessment of sustainability performance in the UWS is a major challenge for filling this gap. In fact, the sustainability performance are related to measuring not only the footprint of the UWS (i.e. the environmental consequences of feeding volumes of inputs and the focus on the outputs), but also its metabolism, i.e., the environmental consequences of how those inputs are transformed into outputs (Beck *et al.*, 2012). The assessment of UWS metabolism from a sustainability-related standpoint is of paramount importance owing to the fact that the understanding of accumulation processes in the urban metabolism is essential for the sustainable development of cities (Kennedy *et al.*, 2007). More specifically, urban metabolism concept, originally developed by Wolman (1965), deals with the quantification of the overall fluxes of energy, water, materials, nutrients and wastes into and out of an urban region. Recent studies from some metropolitan regions demonstrate an increasing per-capita metabolism with respect to all fluxes, which is recognised as an issue threatening sustainable urban development (Kennedy *et al.*, 2007). The literature review manifested the major contribution of urban water-related fluxes to all components of urban metabolism (Kennedy *et al.*, 2011).

Despite substantial recent advances in development of urban water management tools, none of them was considered as a truly holistic approach in which the impacts of urban water services in a system component can be evaluated on the overall system performance and external environment (Nair *et al.*, 2014). More specifically, most of the developed conceptual frameworks either consider the modelling between water demand point (starting with potable water from the point where it is delivered) and wastewater systems (Mackay and Last, 2010; Makropoulos *et al.*, 2008; Mitchell and Diaper, 2010; Mitchell *et al.*, 2001) or focus only on water supply systems between water resource and water demand points (Rozos and Makropoulos, 2013). These models have mainly focused on quantification of water flows while other sustainability fluxes such as indirect (embodied) energy fluxes and GHG emissions resulted across the full urban water cycle have been overlooked, or at least not in a systematic and holistic framework. The concept of UWS metabolism was recently introduced by Venkatesh *et al.* (2014) using an annually based dynamic metabolism model (*DMM*). However, no water or any other flow is simulated within the individually separated system components in the *DMM* and the environmental impacts are quantified by multiplying annual water production for each of the system components by a suitable conversion factor.

This paper aims to extend the metabolism-based modelling concept outlined here for deriving an integrated, conceptual simulation model based on specific UWS system representation involving all of its principal components and subsystems (i.e. water supply, water demand, sewer and drainage subsystems). This integrated model is called WaterMet$^2$ (where 'Met' stands for both metabolism and metropolitan hence '$^2$'). This model aims to quantify resource flows in the UWS and consequent environmental impact categories. All this, in turn, will enable undertaking a sustainability assessment of not only the existing UWS but also the UWS modified by some strategic type interventions over a pre-defined long-term planning horizon. In the next section, WaterMet$^2$ methodology is described in which the main features and modelling approach are explained in further details. Then, the application of the developed model to the case study is explained and the obtained results are discussed. Finally, the conclusions are drawn and some future work recommendations are made.

## 2. Methodology

### *2.1. General WaterMet$^2$ modelling concept*

WaterMet$^2$ is a conceptual, simulation-type, mass-balance-based model which quantifies metabolism related performance of the integrated UWS with focus on sustainability-related issues. Metabolism in the UWS refers to all kinds of flows and fluxes (e.g. water, energy, materials and so on) required to fulfil the business-as-usual UWS functions (Behzadian *et al.*, 2014b). The integrated modelling implies the simulation of the key processes and components in urban water services as a complex and interrelated system. The main functionality and complexity of WaterMet$^2$ for calculating water-related flows is similar to the previously developed tools such as *UVQ* (Mitchell and Diaper, 2010), *UOWT* (Makropoulos *et al.*, 2008) and *CWB* (Mackay and Last, 2010). However, once the water-related flows are quantified for each component by simulating the integrated UWS for each time step in WaterMet$^2$, other fluxes (Fig. 1) are quantified based on impact coefficients presented by Venkatesh *et al.* (2014). This capability of WaterMet$^2$ (i.e. quantifying other metabolism based fluxes, especially the environmental impact categories within the simulation of the integrated UWS) makes it distinct from other counterpart models. The principal water flow routes, storages, sources and sinks modelled in WaterMet$^2$ are also illustrated in Fig. 2. A daily mass balance based approach is used for modelling water flows and other fluxes outlined below. The water sources and sinks are the water boundaries. The water storages (e.g. service reservoirs) and flow routes (e.g. trunk mains) stand for any physical assets with the capability of storing and conveying water within the urban area, respectively (see Table 1 for description of their functionality). Also note that despite the fact that life cycle assessment comprises two phases of infrastructure and operation (Fagan *et al.*, 2010), WaterMet$^2$ only deals with the functions in the operation (i.e. use) phase of the UWS due to insignificant environmental impacts of infrastructure activities such as construction, installation and demolition (Lundin and Morrison, 2002; Lundie *et al.*, 2004).

### *2.2. Spatial UWS representation*

An UWS comprised of three major subsystems (i.e. water supply, stormwater and wastewater) is represented using four spatial scales in WaterMet$^2$ to simulate the principal flows and processes (Fig. 2): (1)

System area; (2) Subcatchment area; (3) Local area; (4) Indoor area. The main typical components of the UWS infrastructure listed in Table 1 (e.g. distribution mains and sewer networks) are defined only in the System area scale. Water flow between these components comprising the three subsystems is also modelled at System scale in WaterMet$^2$ (see Figs. 2 and 3). Other scales outlined below are used to define input data required for modelling further details of urban water cycle beyond the UWS infrastructure.

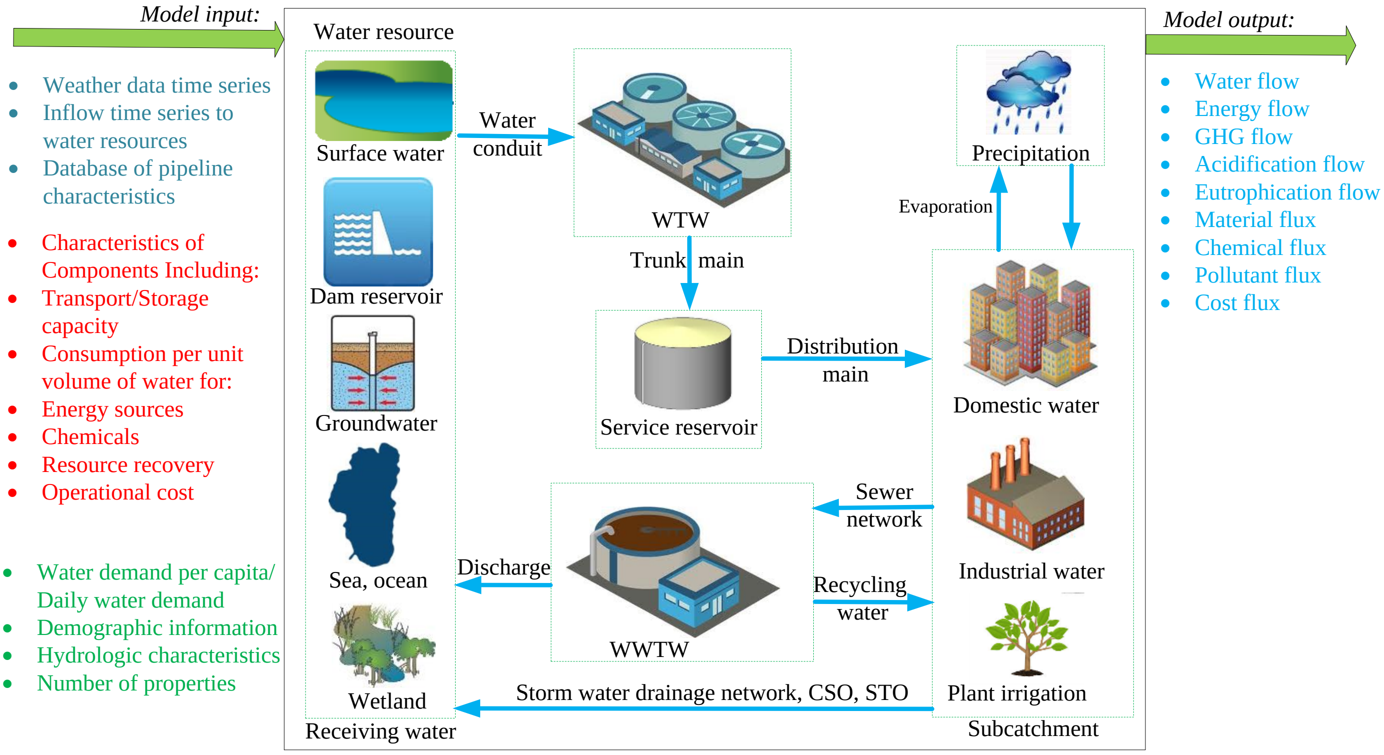

**Fig. 1.** Main components, processes, inputs and outputs of an urban water cycle used for modelling in WaterMet$^2$

The System area spatially can be split up into a number of Subcatchments, which make the use of a distributed model for the UWS. This split is essentially carried out based on the urban drainage system considerations (i.e. topology and gravity in stormwater/wastewater collection systems). Subcatchments serve as 'collection points' in both simplified water supply and separate/combined sewer subsystems. Two main physical components particularly defined on this level are Subcatchment RWH and GWR tanks (Table 1). The Subcatchment area in WaterMet$^2$ is used to represent a group of neighbouring Local areas. The Local area shown in Fig. 2 is defined as a group of similar typical households/properties (Indoor scale) with a surrounding area. A Local area 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 surfaces, impervious surfaces and water bodies (e.g. lake and river). The main tasks of the Local area are to handle water demands, rainfall-runoff modelling and on-site water treatment options. In addition to the per capita water demand specified at Indoor areas, other types of water demand (e.g. irrigation, industrial/commercial usage) can be defined at this scale based on the average daily consumption per Local area. WaterMet$^2$ uses the rainfall-runoff modelling approach inspired by the Rational Method (Maidment, 1992). Two water recycling schemes including Local rainwater harvesting (RWH) and grey water recycling (GWR) can be defined at this scale. In addition, the sum of wastewater/stormwater collected from different inside local areas in a Subcatchment is delivered to sewerage and represented as wastewater/stormwater of the relevant Subcatchment.

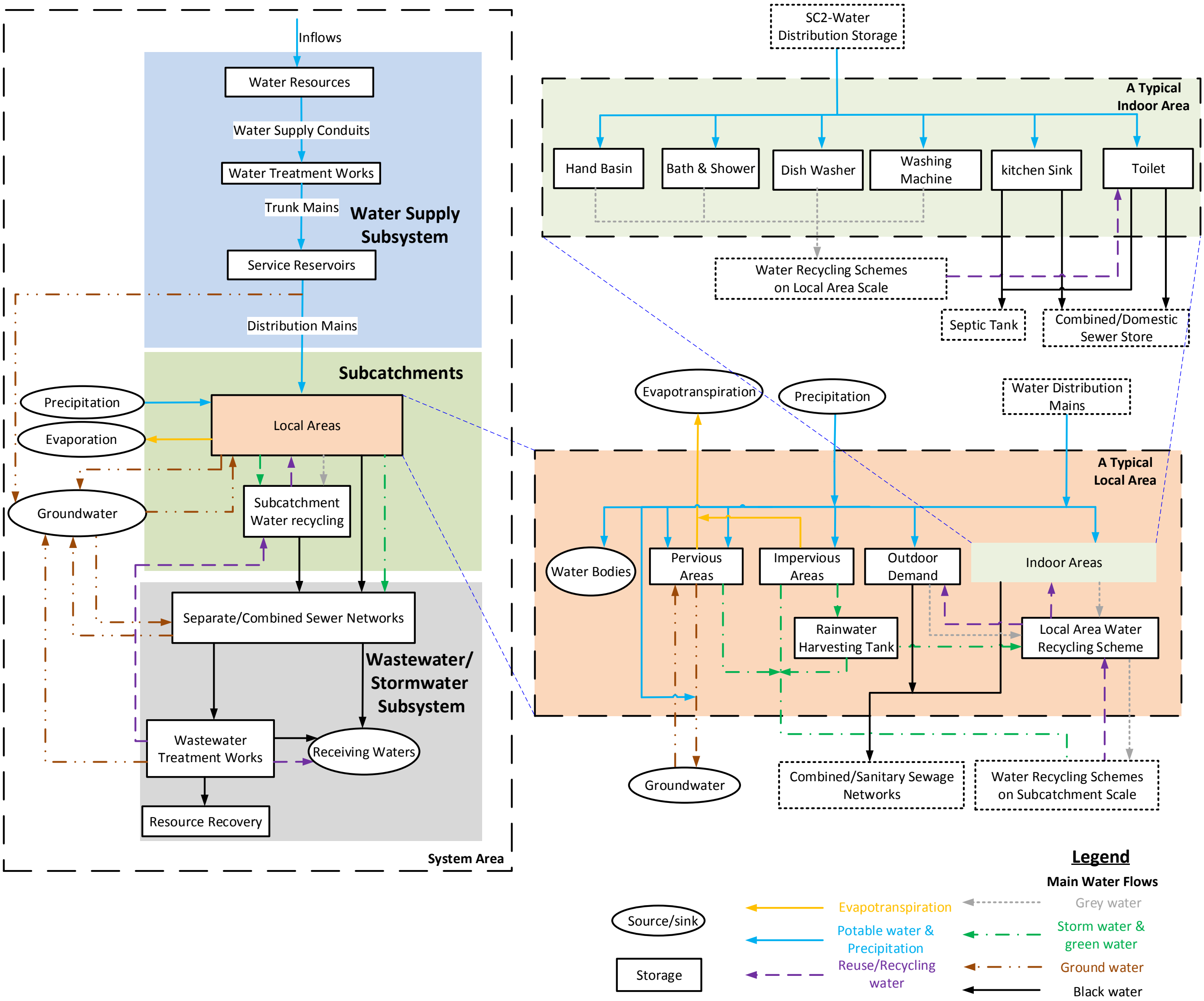

**Fig. 2.** Principal flow routes, storages and sources/sinks in WaterMet$^2$ and its spatial representation.

The Indoor area, as the smallest spatial scale in WaterMet$^2$, represents a single property, specifically a household, without any surroundings (e.g. gardens or public open outdoor spaces). Not only residential areas, but any other type of property (e.g. residential, industrial, commercial, public, etc.) can also be represented at this scale. Indoor water demand profiles are defined at this scale based either on the daily average water demand per capita or on detailed information of the water consumption for residential appliances and fittings (Mackay and Last, 2010). For the latter case, the Indoor scale provides the possibility of defining six types of appliances and fittings as (1) hand basin, (2) bath and shower, (3) dish-washer, (4) washing machine, (5) kitchen sink and (6) toilet.

**Table 1** Description and spatial levels of various components and processes modelled in WaterMet$^2$

| **Component** | **Description** | **Spatial Level In WaterMet$^2$** | | | |
|---|---|---|---|---|---|
| | | System area | Subcatchment area | Local area | Indoor area |
| **Water supply conduits (SC)** | Conveyance of raw water from water resources to WTWs | ✓ | | | |
| **Trunk mains (TM)** | Conveyance of potable water from WTWs to service reservoirs | ✓ | | | |
| **Distribution mains (DM)** | Distribution of potable water from service reservoirs among water consumption points | ✓ | | | |
| **Combined/separate sewer networks (SN)** | Collection of sanitary sewage/ stormwater runoff and conveyance to WWTWs/receiving waters | ✓ | | | |
| **WTWs, WWTWs** | Treatment of raw water and wastewater | ✓ | | | |
| **Service reservoirs (SR)** | Potable water storage prior to distributing among the costumers | ✓ | | | |
| **Water resources (WR)** | Raw water storage | ✓ | | | |
| **Grey water recycling tank** | Collection and treatment of grey water from water consumption points for water reuse | | ✓ | ✓ | |
| **Rainwater harvesting tank** | Collection and treatment of rainwater from impervious areas for water reuse | | ✓ | ✓ | |
| **Rainfall-runoff modelling** | Conversion of precipitation to surface runoff based on hydrologic specifications | | | ✓ | |
| **Water consumption points** | Indoor and outdoor water usages | | | ✓ | ✓ |

## *2.3. Temporal UWS representation*

As the aim is to support strategic planning, WaterMet$^2$ adopts a daily simulation time step to track down all the modelled flows/fluxes (Mackay and Last, 2010; Mitchell and Diaper, 2010). Simulation of smaller time step (e.g. sub-daily) has been proposed by some models (Makropoulos *et al.*, 2008; Fagan *et al.*, 2010) but it requires excessive computational effort while the impact on the water supply reliability has been insignificant (Paton *et al.*, 2014). On the other hand, considering a bigger time step (e.g. monthly) may result in the inaccuracy of the results for the components with a small tank capacity. For instance, RWH tanks with a capacity which is typically of much smaller than water resource capacities can better capture highly fluctuated variations of daily rainfalls. The UWS performance is then simulated typically for a long-term period of time according to the defined planning horizon. Consequently, time series-based input data in WaterMet$^2$ (i.e. weather data and inflow to water resources) need to be provided on a daily basis for the time period being analysed.

### *2.4. Principal WaterMet$^2$ flows/fluxes*

WaterMet$^2$ within the UWS components tracks down nine principal flows/fluxes including water, energy, GHG, acidification, eutrophication, material, chemical, pollutant and cost which are outlined below. The flows can be aggregated temporally and spatially within the entire UWS to derive the basic performance metrics shown in Table 2.

*Water flow*: WaterMet$^2$ recognises various types of water streams (i.e. potable water, green water, greywater, reuse/recycling water, black water/wastewater and groundwater) which are described in appendix I (Makropoulos *et al.*, 2008). The main streams of water flow shown in Fig. 2 are simulated first at different components as a basis for calculating other dependent flows in WaterMet$^2$. Clean (potable) water originated from water resources is the only water flow used in water supply and is terminated at water consumption points. Precipitation on both impervious and pervious areas generates stormwater which can be converted to either green water if collected by RWH tanks or wastewater if discharged into sewer networks. If GWR scheme is employed, grey water flow is collected from all assigned water consumption points except toilet and kitchen sink. Recycling (reuse) water flow is then denoted as treated grey/green water by either centralised (i.e. WWTWs) or decentralised (e.g. GWR tanks) schemes. Otherwise, black water is discharged into septic tanks/sewerage and eventually treated in WWTWs. Daily evapotranspiration based on the "preferred" method (Maidment, 1992) is used in WaterMet$^2$ to estimate the evaporated flow which is then subtracted from the height of rainfall and snowmelt before the amount of generated runoff is calculated.

*Energy flux*: WaterMet$^2$ analyses different sources of energy resulted from resources either consumed (e.g. transmission and treatment) or recovered in the UWS components which are listed in Table 3. The consumed energy resulted from resources consumed is either direct (i.e. fossil fuel and electricity) or indirect (i.e. embodied energy in materials and chemicals). The recovered energy is obtained from substituted fuels, wastewater treatment by-products in WWTWs and generated electricity from either biogas combustion in WWTWs or micro-turbines in water distribution networks. While analysing energy within the UWS components, the energy associated with household water end-users (e.g. water heating for appliances and fittings) is not taken into account in calculation of energy flow in WaterMet$^2$.

*GHG flux*: This indicator is considered in WaterMet$^2$ due to its dominant factor in climate change and significant effect on other environmental impact categories (Change 2007). Both caused and avoided GHG emissions are calculated in WaterMet$^2$ according to Global Warming Potentials with a 100-year time horizon (GWP 100) presented in IPCC (2006). Table 4 gives a list of GHGs (i.e. carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) gases) emitted from different UWS components. These modelled emissions are divided into three groups: (1) $CO_2$ gas emitted (caused GHG) either directly (e.g. fossil fuel combustion) and indirectly (e.g. embodied bodies in materials and chemicals) in all UWS components; (2)

$CO_2$ gas avoided from the resource recovery in some UWS components (e.g. saving embodied energy of urea production obtained from recovering urea in WWTWs) and (3) emitted $CH_4$ and $N_2O$ gas resulted from treatment processes in WWTWs (Metcalf and Eddy 2003). GHG emissions expressed in kg $CO_2$ equivalent ($CO_2$-eq) are equal to 1 for $CO_2$, 25 for $CH_4$ and 298 for $N_2O$ (Change 2007).

**Table 2** Basic metrics derived from flows/fluxes quantified by WaterMet[2] and the relevant UWS components

| **Flow/flux** | **Metric** | **UWS components**[1] | **Sources** |
|---|---|---|---|
| Water | Water demand (total, potable, delivered, undelivered, delivered rainwater, delivered recycling water, domestic, industrial, irrigation, frost tapping, unregistered public use) | SC, UWS | Mitchell *et al.*, 2001;<br>Makropoulos *et al.*, 2008;<br>Mackay and Last, 2010;<br>Behzadian *et al.*, 2014c |
| | Inflow (clean water, stormwater, grey water, wastewater, treated/untreated wastewater) | WR,WSC,WTW,TM, SR, DM, SN, WWTW, SRWH, SGWR, LRWH, LGWR, RW | |
| | leakage | WR,WSC, DM, UWS | |
| | Outflow (delivered, undelivered, treated) | WR,WSC, WTW, TM, SR, DM, SRWH, SGWR, LRWH, LGWR | |
| | volume, loss, overflow | WR, WTW, SR, WWTW, SN, SRWH, SGWR, LRWH, LGWR | |
| | STO, CSO, excess stormwater, excess wastewater | SN, UWS | |
| Energy | Total, electricity, fossil fuel, embodied | All components, UWS | Mitchell and Diaper, 2010;<br>Venkatesh, and Brattebø, 2012 |
| GHG | Total, $CO_2$-based (total, electricity, fossil fuel, embodied), caused, avoided | All components, UWS | Change, 2007;<br>Venkatesh *et al.*, 2014 |
| | $CH_4$-based, $N_2O$-based | WWTW, UWS | |
| Acidification | Total, $SO_2$-based (total, electricity, fossil fuel, embodied), caused, avoided | All components, UWS | Tukker and Jansen 2006;<br>Venkatesh *et al.*, 2014 |
| | $NH_3$-based, $NO_2$-based, | WWTW, UWS | |
| Eutrophication | Total, $PO_4$-based (total, electricity, fossil fuel, embodied), caused, avoided | All components, UWS | Tukker and Jansen, 2006;<br>Venkatesh *et al.*, 2014 |
| | $NH_3$-based, $NO_3$-based, COD to water, Phosphorous with effluent | SC, SN, WWTW, RW, UWS | |
| Material | Mass, length | DM, SN, UWS | Venkatesh, 2012 |
| Chemical | Mass | WTW, SR, WWTW, UWS | Mitchell and Diaper, 2010; |
| Pollutant | Contaminant load (inflow, outflow), generated sludge | SN, WWTW, SRWH, SGWR, LRWH, LGWR, RW, UWS | Mitchell and Diaper, 2010;<br>Behzadian and Kapelan, 2013 |
| | Contaminant load (total, treated WWTW outflow, untreated WWTW outflow, untreated STO) | SN, WWTW, RW, UWS | |
| Cost | Operational | All components, UWS | Behzadian and Kapelan, 2013 |

[1] Please see appendix I for the notations used in this Table.

*Acidification/eutrophication flux*: Acidification and eutrophication (also known as nutrification) potentials are considered in WaterMet$^2$ because they are the most major impact categories in urban water cycle services compared to other commonly used environmental impact categories (Venkatesh and Brattebø 2012). Three major acidifying gas emissions in water systems are sulphur dioxide ($SO_2$), ammonia ($NH_3$) and nitrogen dioxide ($NO_2$) (Tukker and Jansen 2006) which are calculated in WaterMet$^2$ as caused and avoided acidification flux. Eutrophication flux is calculated by WaterMet$^2$ as emissions to both atmosphere and water in the forms of ammonia gas, nitrate to water, COD to water and phosphorous with effluent as listed in Table 4 in the UWS components. Acidification and eutrophication fluxes are finally converted and expressed in kg of $SO_2$-eq and $PO_4$-eq, respectively. Characterisation factor for each kg of the above gases to these equivalent units were extracted from the *DMM* (Venkatesh *et al.,* 2014) and equal to 2.45 for $NH_3$ and 0.56 for $NO_2$ in acidification and 3.8 for ammonia, 4.4 for nitrate, and 1 for COD in eutrophication.

**Table 3** Consumed and recovered resources modelled by WaterMet$^2$ in the relevant components

| | **Source type** | **Instances supported by WaterMet$^2$** | **WaterMet$^2$ UWS components$^1$** |
|---|---|---|---|
| Resource consumed | Electricity | Electricity from grid | All components |
| | Fossil fuel | Coal, diesel, fuel oil, gasoline, LPG, natural gas and wood | All components |
| | Material | Polyvinyl chloride (PVC), polyethylene (PE), mild steel, ductile iron, grey cast iron, concrete, epoxy resin, polyurethane (PUR), copper, polypropylene (PP) | WSC, TM, DM |
| | Chemical | Alum, carbon dioxide, calcium hydroxide, PAX, sodium hypochlorite, chlorine, iron (ferric) chloride, iron (ferric) sulphate, nitric acid, methanol, ethanol, sodium hydroxide, potassium permanganate, ozone, silica sand/micro-sand | SR, WTW, WWTW |
| Resource recovered | Substituted fuel | Heat, transport fuel | WWTW |
| | By-product | Ammonium nitrate, urea, single superphosphate, biogas | WWTW |
| | Electricity generated | Electricity generated from biogas combustion | WWTW |
| | | Electricity generated from micro-turbine | WSC, TM, DM |

[1] Please see appendix I for the notations used in the Table

*Material flux*: WaterMet$^2$ tracks down only those pipeline materials which are used in the operation (i.e. rehabilitation), not in the construction of either the existing infrastructure or any new development. Thus, WaterMet$^2$ quantifies the impacts of the material flux on other fluxes/flows (environmental impacts and cost) according to the approach suggested by Venkatesh (2012) using a number of key features of pipeline (i.e. length, material, diameter and age). The environmental impacts in the material flux basically originate from both direct (e.g. fossil fuel used for rehabilitation) and indirect (e.g. embodied energy) causes

(Behzadian *et al.*, 2014b). These impacts can be due to either interventions (e.g. rehabilitation of existing pipes) or simply long-term ageing (i.e. 'doing nothing') of the UWS infrastructure.

*Chemical flux*: WaterMet$^2$ quantifies the environmental impacts of a number of chemicals (listed in Table 3) which are used for treatment purposes in some UWS components (WTWs, WWTWs and service reservoirs). The impacts in those components mainly stem from the embodied energy of chemicals. The consumption of ethanol and methanol in WWTWs for wastewater treatment processes can directly emit $CH_4$ gas and thus cause GHG emissions (Table 4).

**Table 4** Caused and avoided environmental impacts modelled by WaterMet$^2$.

| | |
|---|---|
| GHG emissions | Caused and avoided $CO_2$ equivalent from resources consumed and recovered in Table 3 |
| | Caused $CO_2$ gas emissions from using methanol and ethanol in WWTW |
| | Caused $CH_4$ gas emissions from incomplete biogas combustion in WWTW |
| | Caused fugitive $CH_4$ gas emissions from sludge end-users (landfill and fertiliser) in WWTW |
| | Caused fugitive $N_2O$ gas emissions from sludge end-users (landfill and fertiliser) in WWTW |
| | Caused $N_2O$ gas emissions during wastewater treatment in WWTW |
| Acidification | Caused and avoided $SO_2$ equivalent from resources consumed and recovered in Table 3 |
| | Caused fugitive $NH_3$ gas emissions from sludge end-users (landfill and fertiliser) in WWTW |
| | Caused $NH_3$ gas emissions from incomplete biogas combustion in WWTW |
| | Caused $NO_2$ gas emissions from incomplete biogas combustion in WWTW |
| | Caused $SO_2$ gas emissions from biogas combustion in WWTW |
| Eutrophication | Caused and avoided $PO_4$ equivalent from resources consumed and recovered in Table 3 |
| | Caused fugitive $NH_3$ gas emissions from sludge end-users (landfill and fertiliser) in WWTW |
| | Caused phosphorous content of effluent in Table 2 |
| | Caused carbon content (COD) of effluent in Table 2 |
| | Caused nitrogen (nitrate) content of effluent in Table 2 |

*Pollutant flux*: Water quality modelling in WaterMet$^2$ is confined to stormwater and wastewater subsystems (Makropoulos *et al.*, 2008). While a simplified water quantity modelling assumes a daily mass balance of the water flows without any travel time of water quality routing, sequential daily water quality modelling allows tracking of any contaminant loads. Hence, a daily flux of user-defined pollutants is used in WaterMet$^2$ and expressed as load of contaminants (kg/day). The modelling is based on the source-sink concept and complete mixing assumptions with no dispersion, diffusion, decay or growth for pollutants (Mitchell and Diaper, 2010). Hence, a user-defined pollutant load is tracked down wherever generated (i.e. wastewater or runoff) or removed (i.e. treatment) once reaching a sink (i.e. receiving waters).

*Cost flow*: WaterMet$^2$ directly calculates operational and maintenance (O&M) costs as either fixed (e.g. labour and maintenance) or variable (e.g. electricity) within the UWS components. The user-defined annual fixed costs is converted into the equivalent daily values for calculation of cost flow. Variable operating costs are defined based a unit volume of water consumed and calculated accordingly for each component after simulating the daily water flow. To derive the financial metrics especially for comparing different intervention strategies added at different periods of time, WaterMet$^2$ can discount the cost flow to any specific times based a pre-defined interest rate.

### *2.5. Modelling of principal UWS components in WaterMet$^2$*

Potable water supply and collection of wastewater and stormwater are handled in WaterMet$^2$ through a simplified but integrated approach of a distributed model comprised of the three subsystems shown in Fig. 3. The water supply in WaterMet$^2$ comprises three types of ‘storage’ components (i.e. water resources, WTWs and service reservoirs) and three types of ‘flow route’ elements including water supply conduits ($SC$), trunk mains ($TM$) and distribution mains ($DM$). Subcatchments serve as water consumption points for water supply and wastewater/stormwater collecting points for wastewater/stormwater subsystems. Other key components modelled in the wastewater /stormwater subsystems are separate/combined sewer networks ($SN$) as flow route, WWTWs as storage, receiving waters as sink. Wastewater and runoff generated in Local areas are aggregated to Subcatchment ‘points’ where they are delivered to flow routes in the relevant Subcatchment sewer networks.

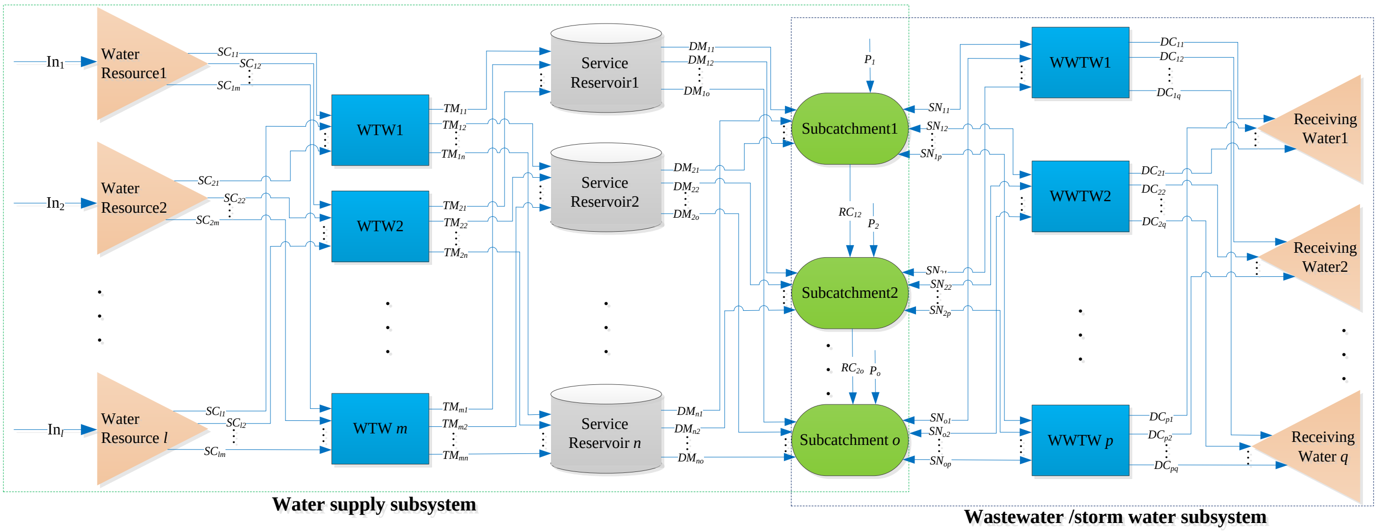

**Fig. 3.** Schematic representations of the main ‘storage’ and ‘flow route’ components modelled in WaterMet$^2$

Simulation of the water supply subsystem in WaterMet$^2$ follows a two-step approach of a typical water supply system (Loucks *et al.*, 2005). The first step deals with the calculation of daily water demand in the modelled components starting from the most downstream points (i.e. Local areas/Subcatchments) aggregated up to the most upstream points (i.e. water resources). The calculated water demands are added by leakages of conveyance elements (Mitchell and Diaper 2010). For instance, the daily volume of water demand for water resource $i$ and day $t$ ($RD_{it}$) is calculated in Eq. (1) by adding the leakage percentage pertaining to conduit $SC_{ij}$ ($CL_{ij}$) to the water demand of that conduit:

$$RD_{it} = \sum_{j=1}^{m} CF_{ij} \times WD_{jt} \left(1 + CL_{ij}/100\right) \quad (1)$$

where $WD_{jt}$=water demand of WTW $j$; $CF_{ij}$= pre-specified fraction of water demand in resource $i$ from WTW $j$ by conduit $SC_{ij}$; $m$=number of WTWs. Once the water demand of water resources is determined, the second step starts off with water withdrawal and conveyance to downstream elements sequentially in which capacity control of storage components (i.e. both minimum and maximum) are the only governing equations. The released/abstracted water is finally distributed among Subcatchments and consequently water consumers. Mass balance relationship expressed in Eq. (2) is applied to calculate the water volume of a storage component in consecutive days:

$$S_{i,t+1} = S_{i,t} + I_{i,t} - D_{i,t} \quad (2)$$

where $S_{i,t}$ and $S_{i,t+1}$ =volume of component $i$ for day $t+1$ and $t$, respectively; $I_{i,t}$=inflow to component $i$ for day $t$ and $D_{i,t}$=output for component $i$ for day $t$. After water consumption, a percentage of consumed water (typically over 90% for domestic and 85-95% for non-domestic (Metcalf and Eddy, 2003)) is converted to sanitary sewage (grey water or black water) and the rest is assumed to be lost. The stormwater runoff and sanitary sewage in the local areas of each Subcatchment are aggregated at the Subcatchment outlet point where they are collected by sewer flow routes in the conceptual sewer subsystem (Fig. 3). The wastewater are then delivered to WWTWs based on the pre-specified fraction for each sewer network flow route ($SN_{ij}$). Finally, the treated wastewater flow is either discharged into receiving water bodies based on a pre-specified fraction for each discharge route ($DR_{ij}$) or recycled to Subcatchments for water reuse. Once the daily water flow rate is calculated for each component based on the methodology outlined above, other flows/fluxes dependent to water flow (e.g. energy and GHG emissions) are calculated by multiplying the amount of the water conveyed/treated by a constant flux consumed per unit volume of water, which is specified as input data of WaterMet$^2$.

### *2.6. Data requirement in WaterMet$^2$*

A WaterMet$^2$ model is constructed based on an arbitrary number of UWS components for each type (Fig. 3). The key functional characteristics of each component are required as input data, e.g. storage and transport capacity, energy and cost per unit volume of water (Behzadian *et al.*, 2014c). Water demand profiles as well as their temporal variations over the planning horizon need to be defined to consider seasonal and annual fluctuations. The former is defined using a consumption pattern in a year and the latter is defined based on a time-series of annual population growth in Local areas. The WaterMet$^2$ spatial scales (e.g. number of Subcatchments /Local areas) can provide more flexibility for defining the analysed system. More specifically, these scales can be used to represent a relatively large (or small) spatial area depending on the size and type of the urban area being analysed and also on the level of spatial resolution required and the available data in different scales. For instance, if there is a lack of available data for defining a variety of Subcatchments in a System area, one can consider the System area with a limited number of Subcatchments bearing in mind that the reduced level of details modelled will have an impact on the accuracy of the calculated flows and associated variables.

## 3. Case Study

### *3.1. Urban water system description*

The case study used here is a real-life urban water system of a northern European city. The application of the WaterMet$^2$ model is demonstrated here on the challenges of a long-term planning for this UWS. The city is likely to face challenges in the future due mainly to population growth. Therefore, it is assumed that the future water demand will increase as a consequence of the highest foreseen rate of population growth in the city, i.e. it is assumed that the city population will increase from approximately 610,000 inhabitants in 2011 to the estimated 1,150,000 inhabitants by 2040. This is likely to impose significant strains on the UWS performance. The existing UWS, as schematically shown in Fig. 4, is fed by two main surface water resources (WR1 and WR2) connected to corresponding WTWs (WTW1 and WTW2) and service reservoirs (SR1 and SR2). These two sources provide fresh water for the city with 90% of water being supplied from WTW1 and 10% from WTW2. The existing distribution networks are connected to the two respective upstream service reservoirs by means of two distribution mains (DM1 and DM2) proportional to the capacity of the existing water supply. Both of the surface water resources, on which the city relies, are of limited capacity (120 and 13.8 million cubic metres (MCM)). The corresponding average annual inflows for WR1 and WR2 are 287 and 12 MCM/year, respectively. The leakage from the Subcatchment pipelines is currently 22% of total water demand. The existing sewer network represents a mix of 37% combined sewers, 30% sanitary sewers and 33% storm drains. Two WWTWs, collecting 63% (WWTW1) and 37% (WWTW2) of the wastewater flows, and sewer network overflows (i.e. CSOs) discharge the treated and untreated wastewater /stormwater into the downstream sea (RW1) as the only receiving water body. The main characteristics of the key UWS components (input data) are presented in Table 5.

The UWS model is represented here as an aggregated model using a single WaterMet$^2$ Subcatchment with a single Local area used to define the water consumption. The water demand of the single Local area is split into domestic, industrial (commercial), garden watering, frost tapping and unregistered public use with the characteristics presented in Table 6. The frost tapping water demand is the water required to flow through the main pipelines in the UWS over the freezing time in the city (i.e. from November 1 until March 31). The unregistered public use water demand is applied for sum of the authorised and unauthorised consumptions which are not accounted for billing customers. The domestic (indoor) water demand per capita in the city is further split into six types of appliances and fittings given in Table 6.

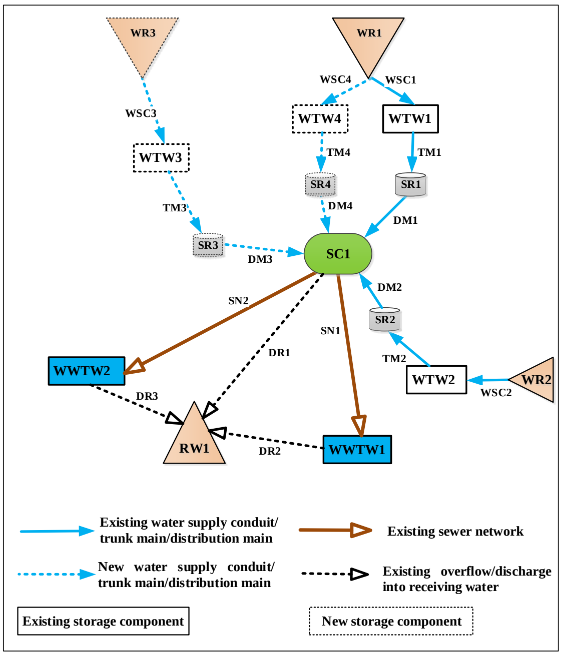

**Fig. 4.** Schematic diagram of the analysed UWS components

**Table 5** Key characteristics of the UWS components

| Component | Capacity (ML/day) | Electricity (kWh/m$^3$) | Fossil fuel (×10$^{-3}$L/m$^3$) | Fixed annual cost (Million €) | Avg. chemical cost (€/m$^3$) |
|---|---|---|---|---|---|
| **WTW1** | 370 | 0.343 | 2.40 | 12.06 | 0.017 |
| **WTW2** | 43.2 | 0.343 | 2.40 | 1.34 | 0.017 |
| **Distribution main** | 413.2 | 0.44 | 3.98 | 13.94 | - |
| **Sewer networks** | 2200* ML | 0.018 | 0.59 | 10.92 | - |
| **WWTW1** | 770 | 0.462 | 0.064 | 6.88 | 0.027 |
| **WWTW2** | 320 | 0.462 | 0.064 | 4.04 | 0.027 |

* Transmission capacity of sewer networks can be defined as either daily transmission capacity in ML/day or storage type transmission capacity with a storage capacity in Million Litre (ML). For the latter, daily transmission release ($Q$) is defined as a function of available volume ($V$) as $Q=a\times V^b$ where $a$ and $b$ are the parameters which are adjusted in the model calibration. Here, storage type transmission capacity is employed with calibrated parameters of $a$=0.2 and $b$=1.0

**Table 6** Input parameters of the UWS water demands

| Parameter description | Value | Appliances and fittings of indoor area | % of indoor water demand |
|---|---|---|---|
| Number of households in year 2011 | 320,000 | Dish washer | 3.2 |
| Average occupancy per household | 2.35 | Hand basin | 12 |
| Indoor water demand | 180 L/day/capita | Kitchen sink | 12.8 |
| Industrial water demand | 54.8 ML/day | Washing machine | 16 |
| Garden watering demand | 63.5 ML/day | Shower | 25 |
| Frost tapping water demand | 35 ML/day | Toilet | 30 |

### *3.2. WaterMet$^2$ model building and calibration*

The WaterMet$^2$ model used in the case study presented here was built by a single person over a period of 12 months once the relevant data was provided by the water company. After model building, the model was then calibrated by using the historical daily measurements for both water and wastewater production. Here, a manual, trial and error approach was employed to calibrate both water supply and stormwater/wastewater subsystems sequentially. Water supply subsystem was first calibrated and validated by using the available data (i.e. two years of recorded daily water production at the WTWs split into two periods using 2011 for calibration and 2012 for validation). The calibration parameters for water supply part include: (1) monthly coefficients of water demand profiles; (2) percentage contribution of daily temperature in daily variation of water demand profiles. The stormwater/ wastewater subsystem was 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 (i.e. perviousness, imperviousness and rainfall-runoff coefficients) and the principal hydraulic features of the WWTWs and sewer networks (i.e. storage capacity). Fig. 5 shows a graphical comparison of the model performance for the validation period in both subsystems plotting the simulated versus observed values. Although both graphs show a fair amount of scatter around the 1:1 slope line, the simulated results in both parts of the integrated model are reasonably close to the observed values. Furthermore, Fig. 6 shows the performance of the stormwater/ wastewater part of the WaterMet$^2$ model during the calibration and verification periods based on a comparison between observed and simulated values. As it can be seen from this figure, the simulated values match the observed values reasonably close for both hydrographs.

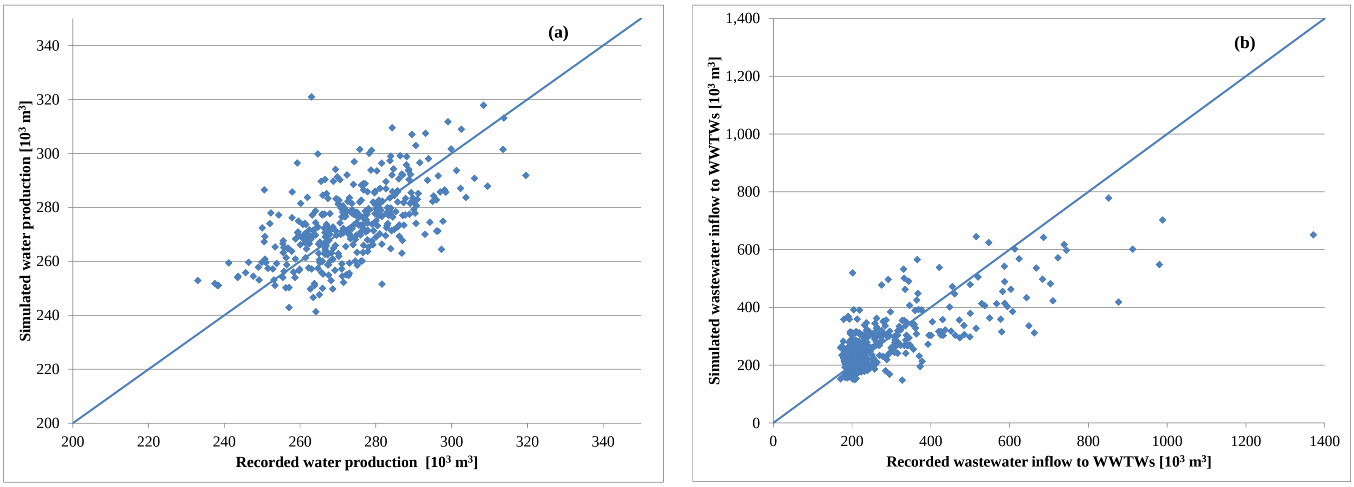

**Fig. 5.** Daily simulated result in WaterMet$^2$ versus recorded values for validation period in (a) water production (b) wastewater inflow to WWTWs

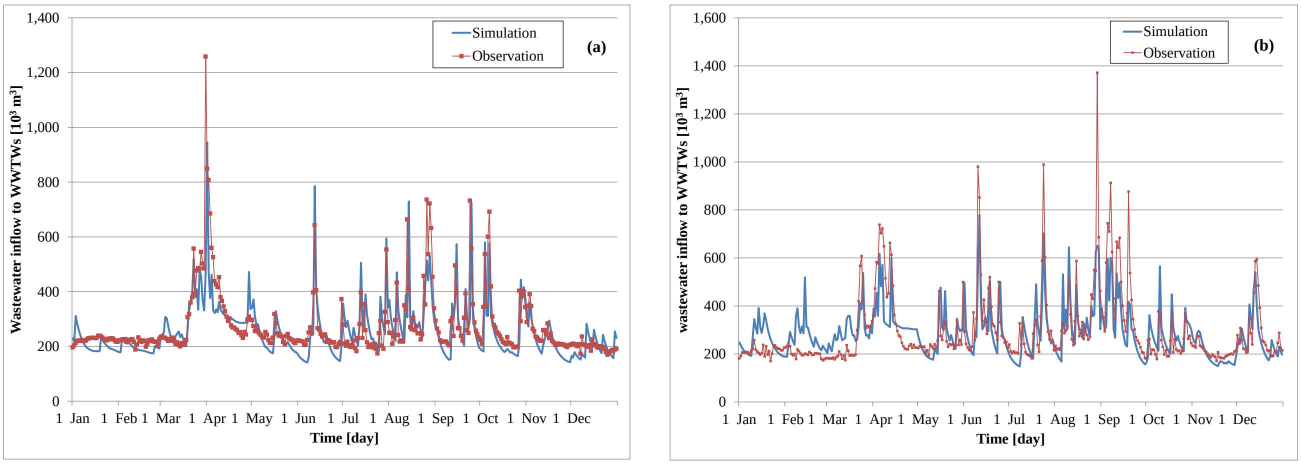

**Fig. 6.** Daily simulated versus recorded wastewater inflow to WWTWs for the periods of (a) calibration (2010) and (b) validation (2011)

Further evaluation of the model performance was undertaken by measuring three quantitative statistics recommended by Moriasi *et al.* (2007): (1) *the Nash-Sutcliffe efficiency (NSE)* with an optimal value of 1.0 and an acceptable range between 0.0 and 1.0; (2) *RMSE-observations standard deviation ratio (RSR) and (3) Percent bias (PBIAS),* both with the optimal value of 0.0. Results of the statistics of the simulated performance (Table 7) indicates a reasonably good prediction accuracy of the wastewater subsystem when compared to the recommended values of hydrologic flows (i.e. NSE ≥ 0.5, RSR ≤ 0.7 and PBIAS < 25%) by Moriasi *et al.* (2007). In addition, the accuracy achieved with the wastewater part of the model is better than the water supply part of the model. This can be attributed to the fact that daily water demands are highly variable over a year, not necessarily corresponding with temperature and calendar monthly variations defined by the WaterMet$^2$ model but other impacts such as human behaviours (e.g. tourism and holidays). Having said this, this is not uncommon and similar accuracy for the water demand based calibration has been reported in previous conceptual models such as *Aquacycle* (Mitchell *et al.*, 2001) and *CWB* (Mackay and Last, 2010). The model accuracy can be improved either by increasing the amount of measured data used in calibration and/or through automated (e.g. optimised) calibration.

**Table 7** Simulation performance of the WaterMet$^2$ model

| | **Water supply subsystem** | | **Stormwater/wastewater subsystem** | |
|---|---|---|---|---|
| | Calibration | Validation | Calibration | Validation |
| **NSE** | 0.25 | 0.22 | 0.51 | 0.56 |
| **RSR** | 0.86 | 0.89 | 0.70 | 0.67 |
| **PBIAS (%)** | -0.50 | -0.30 | 6.02 | 2.45 |

### *3.3. Performance assessment using WaterMet$^2$*

To demonstrate the performance capability of the WaterMet$^2$ model, the metabolism related performance of the UWS is evaluated first assuming business as usual (BAU), i.e. effectively 'do nothing' in the UWS over the planning horizon 2011-2040. The BAU assumes no (capital type) interventions will be implemented in the UWS over the planning horizon under the assumed highest rate of population growth scenario. Therefore, deterioration of the UWS performance such as increased unmet water demand is likely to happen in the BAU. This performance is then compared to the performance of the UWS modified by two different interventions which make the following intervention strategies.

Intervention strategy 1 (S1): the first intervention assumes the "addition of water resources" in year 2020 comprised of a new water resource WR3 (capacity of 13,000 MCM), the two associated WTWs (WTW3 and WTW4) and two corresponding service reservoirs (SR3 and SR4) shown in Fig. 4. Intervention strategy 2 (S2): the second intervention is based on large scale "water recycling" starting in year 2015 and is comprised of adding a single mix of both RWH and GWR schemes at the Local area scale. It is assumed that the RWH scheme collects runoff from roofs, roads and pavements and supplies water only for toilet flushing, garden watering and industrial usages. Each household RWH scheme is assumed to have 3 m$^3$ of tank capacity with an annual operational expense being €72/year (Ward *et al.*, 2012). The electricity required for the operation of the RWH scheme is estimated to be 0.54 kWh/m$^3$ (Ward *et al.*, 2012; Behzadian *et al.*, 2013). A single RWH scheme located in the Local area with an adoption rate of 50% of households assumes to represent many small domestic RWH units across the city. The GWR scheme collects grey water (i.e. from the hand basin, dish washer, shower, washing machine and frost tapping) and recycles the treated grey water for the provision of toilet flushing, irrigation and industrial uses. The electricity consumption for treatment of grey water is assumed to be 1.84 kWh/m$^3$ (Memon *et al.*, 2005). A single representative GWR scheme for 50% of household adoption is assumed to have a total volume of 39,000 m$^3$ with an operational cost of €1.50 million/year.

In general, the performance of the UWS should be evaluated against the agreed-upon criteria derived from the different dimensions of the sustainability framework in water systems including social, environment, economic, governance and assets (Alegre *et al.*, 2012; Morley *et al.*, 2014). For illustrative purposes, the two intervention strategies are compared here with respect to the following sustainability criteria quantified by WaterMet$^2$: O&M cost, percentage of water demand delivered and the three categories of environmental impacts. Note that setting up the case study (e.g. intervention options and metrics) and analysing the results took further 6 months of a single person.

## 4. Results and discussion

The integrated UWS modelled by WaterMet$^2$ is first simulated in the BAU for a period of 30 years starting from 2011 with a daily time step. Due to increasing water demand over the planning horizon, the UWS in the BAU encounters unmet water demand starting from 2013 (Fig. 7). The water undelivered is rather small initially but as the population size increases the water shortage increases eventually up to 27% toward the end of the planning horizon. Following this, the two aforementioned intervention strategies were applied and the modified UWS was simulated using the WaterMet$^2$ model. Comparing monthly percentage of water demand delivered in both intervention strategies indicates that strategy 1 can successfully cope with the increased water demand although a trivial percentage of unmet water demand (3%) occurs during the end years of the planning horizon. However, the delivered water demand obtained in the case of the second strategy, although significantly improved compared to the BAU, is less favourite than the first strategy due to unmet water demand up to 14%. The impact assessment of the two strategies is further carried out using the other WaterMet$^2$ metrics in more details by different components and time scales. The purpose of this distinction is to demonstrate the assessment of the impact of the intervention strategies on different environmental impact categories.

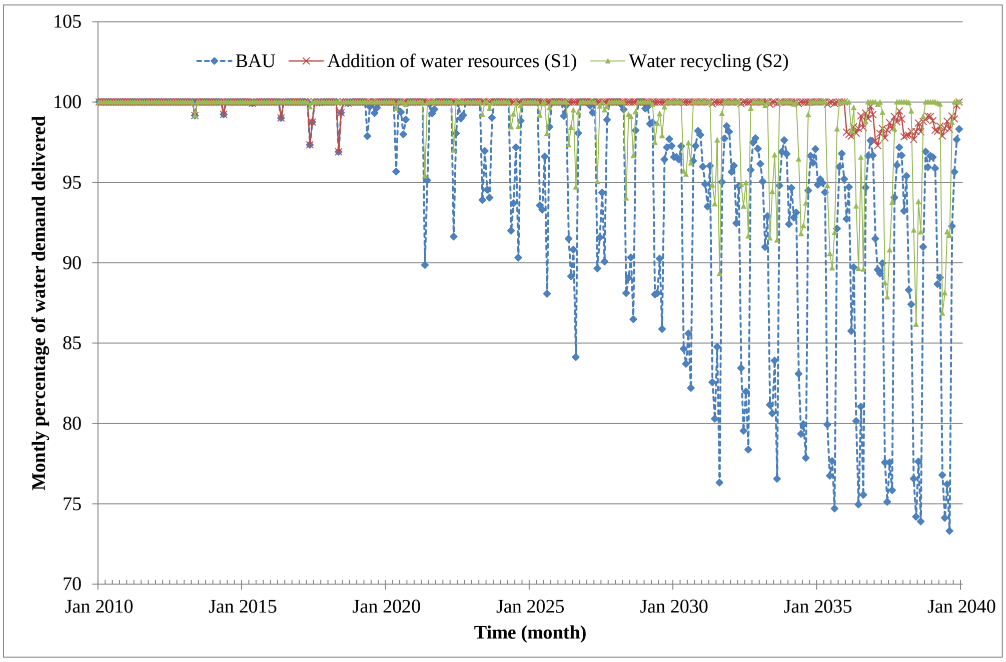

**Fig. 7.** Monthly variations of percentage of delivered water demand over the planning horizon for the analysed strategies

Comparing the GHG emissions resulted from the BAU and other two intervention strategies (Table 8) shows that $CO_2$ is the major factor in emitting GHG (~50%) for all strategies due mainly to the high consumption of electricity and embodied energy within the components especially WWTWs. Almost over one third of all emitted GHG originates from $N_2O$ gas in WWTWs as a result of emissions from treatment processes. While strategy 1 increases 10% the share of GHG emissions in water supply subsystem (from 49 to 54×$10^3$ ton $CO_2$-eq as sum of GHG emissions of WR, WTW and DM in Table 8), it has no effect on the GHG emissions in wastewater/stormwater subsystems. The increased impact in water supply subsystem is expected as this intervention strategy aims to improve the water/supply balance and thus provide more fresh water in the water supply which consequently demands more energy. In spite of improving water supply subsystem by strategy 1, the increased water supplied in this strategy ends up in the increased wastewater/combined sewer subsystem as Dry Weather Flow (DWF). However this additional wastewater would result in an insensible impact on wastewater/stormwater subsystem (i.e. WWTWs and sewer networks) probably due to its partial contribution in wastewater subsystem compared to stormwater flow.

On the other hand, strategy 2 is able to reduce the GHG emissions by approximately 4 and 7 percent in water supply and wastewater/stormwater subsystems, respectively. Overall, the GHG emissions in strategy 1 will increase by almost 2% but can decline in strategy 2 by approximately 7% (Fig. 8(a)). The resulting acidification potentials only refers to $SO_2$ emissions mainly due to energy consumption in the UWS in which WWTWs are accounted for the greatest acidification producer (~90% of the total $SO_2$) as shown in Fig. 8(b). Furthermore, strategy 1 has a negligible impact on increasing acidification of the UWS (~1%) whilst strategy 2 will be able to alleviate it by approximately 10%. All this concludes that WWTWs are the main driver of all sources of GHG emissions (over 77%) and acidification potential (over 88%) in the UWS (Table 8). Therefore, any intervention strategies (e.g. novel technologies) improving the WWTW activities (e.g. biogas recovery efficiency) may play an important role to significantly alleviate the UWS environmental impacts (Zakkour *et al.*, 2002). This corresponds with the previous researches which mainly focused on the reduction in GHG emitted from WWTWs to attain the UWS sustainability (Mouri and Oki, 2010; Nair *et al.*, 2014).

The major sources of eutrophication in the UWS as seen in Table 8 originate from COD to water (~60%) and $NO_3$ to water (~40%). These impacts are mainly owing to overflows of the sewer networks into receiving water bodies compared to treated/untreated discharge of WWTWs. Other sources of eutrophication which result in $PO_4$ emissions are almost negligible compared to the total eutrophication obtained. The contribution of the sewer networks and WWTWs to eutrophication are 55% and 45% of the total amount in the BAU, respectively. Strategy 1 has almost no change to the total eutrophication amount but strategy 2 is able to reduce it by over 20% (see also Fig. 8(c)). This can be attributed to the fact that strategy 2, owing largely to RWH and GWR tanks, can reduce the discharge of contaminants into receiving water bodies. More specifically, the determining factor for reducing eutrophication in this strategy is the 31% reduction in COD discharges from sewer networks, resulted mainly from runoff washing off the contaminant over the urban surfaces. In addition, both recycling schemes directly deteriorate the environmental impact categories due to electricity consumption. However, the major sources of the adverse environmental impacts (e.g. $CO_2$, $N_2O$, $NH_3$, $NO_3$ and COD) in this strategy (S2) have decreased more compared to those in strategy 1 for all components. This can be attributed to the fact that the recycling schemes simultaneously reduce both potable water demand in water supply subsystem and wastewater/stormwater discharged into sewerage and thus indirectly influence the associated environmental impact categories. Consequently, the indirect impacts of this strategy overcome the direct ones.

**Table 8** Simulated performance of the WaterMet$^2$ model

| | | | BAU | | Addition of water resources (S1) | | Water recycling (S2) | |
|---|---|---|---|---|---|---|---|---|
| Environmental impact categries | Emissions | Component | value[1] | percentage [%] | value[1] | percentage [%] | value[1] | percentage [%] |
| GHG emissions | $CO_2$ | WR | 0 | 0 | 2 | 1 | 0 | 0 |
| | | WTW | 31 | 14 | 33 | 14 | 25 | 12 |
| | | DM | 18 | 8 | 19 | 8 | 15 | 7 |
| | | SC | 0 | 0 | 0 | 0 | 7 | 3 |
| | | SN | 1 | 1 | 1 | 1 | 1 | 1 |
| | | WWTW | 65 | 28 | 65 | 28 | 59 | 27 |
| | | Total | **115** | **50** | **120** | **51** | **107** | **50** |
| | $CH_4$ | WWTW | **31** | **14** | **31** | **13** | **28** | **13** |
| | $N_2O$ | WWTW | **82** | **36** | **82** | **35** | **78** | **37** |
| | Total | UWS | **229** | **100** | **233** | **100** | **213** | **100** |
| Acidification | $SO_2$ | WR | 0 | 0 | 3 | 0 | 0 | 0 |
| | | WTW | 72 | 8 | 76 | 8 | 58 | 7 |
| | | DM | 33 | 3 | 35 | 4 | 26 | 3 |
| | | SC | 0 | 0 | 0 | 0 | 13 | 1 |
| | | SN | 2 | 0 | 2 | 0 | 2 | 0 |
| | | WWTW | 851 | 89 | 851 | 88 | 771 | 89 |
| | | Total | **958** | **100** | **967** | **100** | **870** | **100** |
| | $NH_3$ | WWTW | **0** | **0** | **0** | **0** | **0** | **0** |
| | $NO_2$ | WWTW | **0** | **0** | **0** | **0** | **0** | **0** |
| | Total | UWS | **958** | **100** | **967** | **100** | **870** | **100** |
| Eutrophication | $PO_4$ | WR | 0 | 0 | 1 | 0 | 0 | 0 |
| | | WTW | 31 | 0 | 33 | 0 | 25 | 0 |
| | | DM | 9 | 0 | 10 | 0 | 7 | 0 |
| | | SC | 0 | 0 | 0 | 0 | 4 | 0 |
| | | SN | 1 | 0 | 1 | 0 | 0 | 0 |
| | | WWTW | -26 | 0 | -26 | 0 | -24 | 0 |
| | | Total | **15** | **0** | **19** | **0** | **14** | **0** |
| | $NH_3$ | WWTW | **0** | **0** | **0** | **0** | **0** | **0** |
| | $NO_3$ | SN | 1,962 | 10 | 1,962 | 10 | 1,337 | 9 |
| | | WWTW | 5,254 | 28 | 5,254 | 28 | 4,999 | 33 |
| | | Total | **7,216** | **38** | **7,216** | **38** | **6,336** | **42** |
| | COD | SN | 8,475 | 45 | 8,475 | 45 | 5,850 | 39 |
| | | WWTW | 3,227 | 17 | 3,227 | 17 | 2,898 | 19 |
| | | **Total** | **11,701** | **62** | **11,701** | **61** | **8,748** | **58** |
| | Phosphorus | SN | 62 | 0 | 62 | 0 | 41 | 0 |
| | | WWTW | 38 | 0 | 38 | 0 | 34 | 0 |
| | | **Total** | **100** | **1** | **100** | **1** | **76** | **0** |
| | Total | **UWS** | **19,015** | **100** | **19,036** | **100** | **15,173** | **100** |

[1] Unit of the quantity is $10^3$ Ton $CO_2$-eq per capita for GHG emissions, Ton $SO_2$-eq per capita for acidification and Ton $PO_4$-eq per capita for eutrophication. The negative values also imply that avoided environmental impacts is greater than caused ones

Moreover, comparison of the overall O&M costs of the entire UWS (Fig. 8(d)) shows that both strategies would result in a relatively equal growth for O&M costs with an insignificant greater amount for strategy 2. More specifically, the variations of the O&M cost in different UWS components of strategy 1 are almost unchanged except for O&M cost increase in WTWs due to supplying additional raw for treatment. These variations in strategy 2 are also unchanged except for a considerable increase for Subcatchment due to additional costs incurred for water recycling schemes.

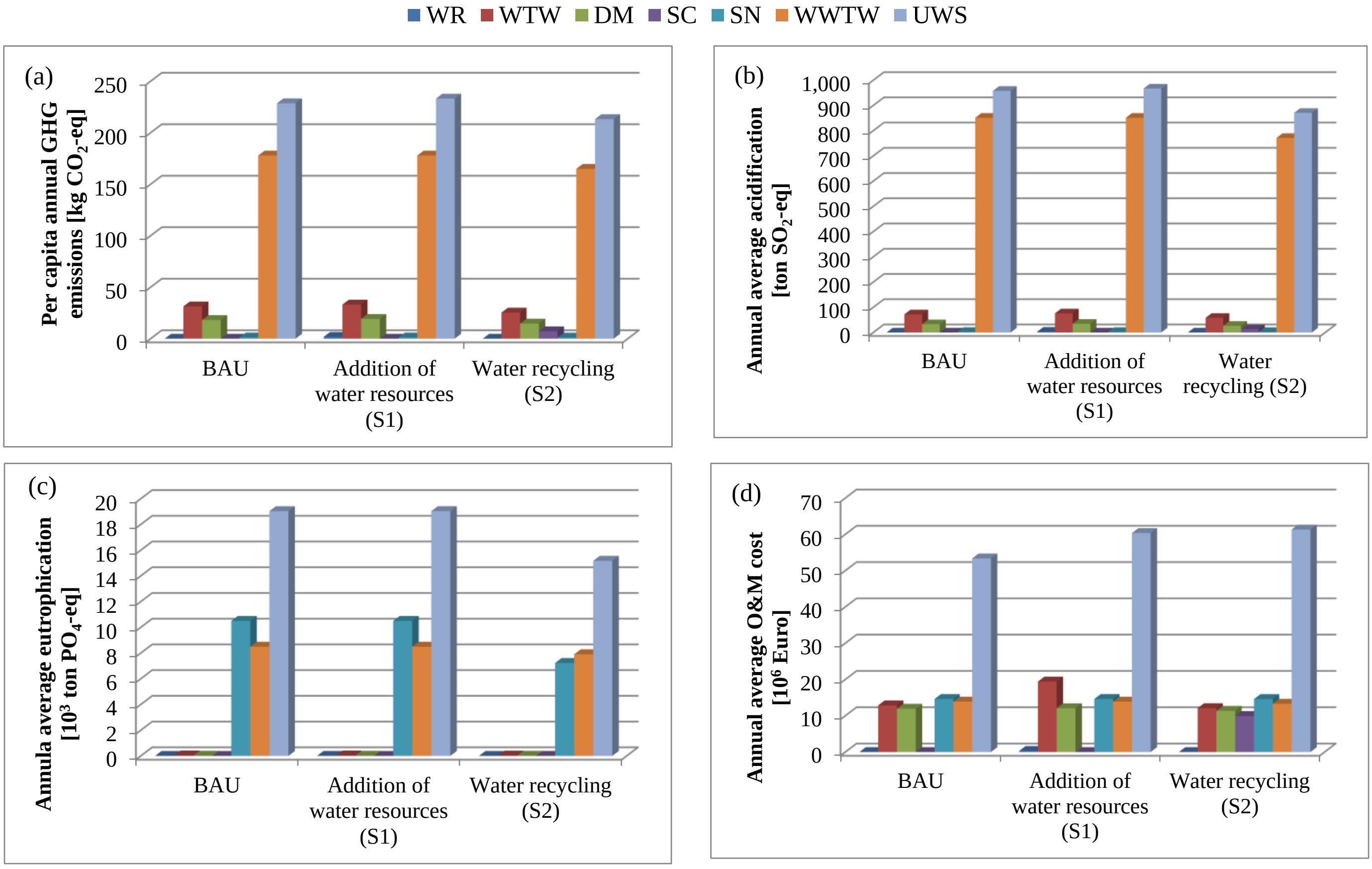

**Fig. 8.** Comparison of the UWS components for different strategies with respect to (a) per capita annual GHG emissions (b) annual average acidification (c) annual average eutrophication (d) annual average O&M cost

Further analysis of the environmental impact categories can be carried out by comparing the annual variations of caused and avoided GHG emissions for the suggested strategies with the BAU (Fig. 9). It is evident that caused GHG emissions in all states are greater than avoided GHG emissions by one order of magnitude. Hence, the effect of avoided GHG emissions is almost negligible for decreasing the total caused GHG emissions in the UWS. After adding a new water resource in year 2020 (strategy 1), the caused GHG emissions have slightly increased although the avoided GHG emissions are unchanged compared to the BAU. However, strategy 2 will significantly mitigate the caused GHG emissions while reducing the avoided GHG emissions at the same rate. Due to the different orders of magnitude between the avoided and caused GHG emissions, consequently the net GHG emissions in strategy 2 will reduce significantly. The decline of the avoided GHG emissions can be attributed to the reduced wastewater /stormwater being conveyed to the WWTWs which are the main factor for the avoided GHG emissions (i.e. by-products of wastewater treatment).

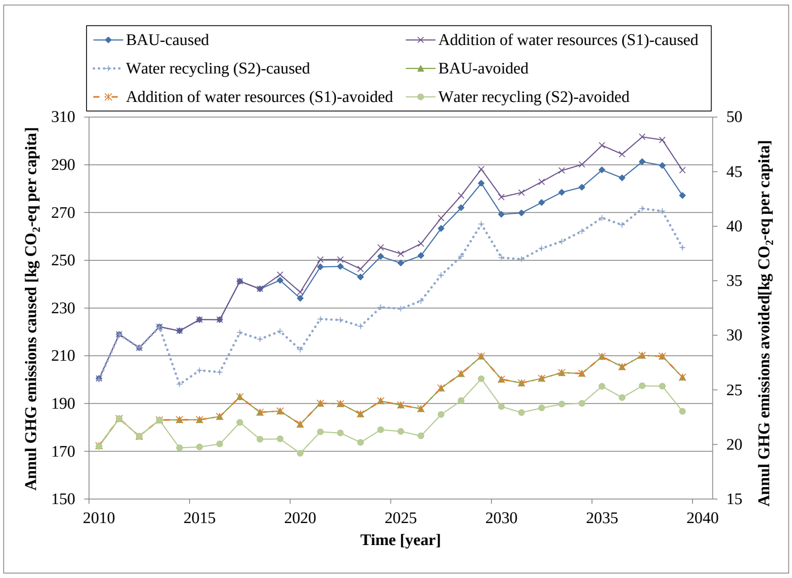

**Fig. 9.** Annual variations of caused and avoided GHG emissions for different strategies

In addition to overall and monthly variations of the metrics in the UWS components, daily analysis of the metrics can uncover some further details of the interaction caused by the intervention strategies. Hence, Fig. 10 shows a snapshot of daily variations for the abovementioned metrics during four months (i.e. January, April, July and October) of year 2038 when the delivered water demand and runoff flow are highly variable. As it can be seen, the variations of some metrics (i.e. GHG emissions, acidification, eutrophication and O&M cost) are mainly affected by runoff variations and directly proportional to runoff. These proportionate fluctuations are particularly evident for the variations of eutrophication which are especially a direct reflection of high daily runoff (compare Fig. 10(a) with 10(d)). This can be due to the contaminants washing off the urban surfaces and discharging into the receiving water bodies. This also confirms the above observation for the total eutrophication of the UWS. Consequently, strategy 1 has no effect on the eutrophication variations while strategy 2 can attenuate the peak values well when there are high daily runoff volumes due to saving of runoff in the storage recycling tanks. The eutrophication improvement for days with no rain is almost trivial compared to the rainy days. However, the impact of either of the two strategies on GHG emissions and acidifications are in opposition. More specifically, while strategy 2 improves daily GHG emissions and acidification, these metrics deteriorate in strategy 1. Furthermore, the rate of variations of these metrics over this period is independent from the daily runoff variations. This rate especially for strategy 1 is more affected by the percentage of water demand delivered according to Fig. 10(e). More specifically, for those days in which the percentage of water demand delivered in the BAU is low, strategy 1 provides more fresh water resulting in more energy consumption. Therefore, GHG emissions and acidification will increase considerably compared to other days. Moreover, increase in the O&M costs in both strategies compared to the BAU is completely independent from either water demand delivered or total daily runoff. The rate of this increase in strategy 1 is greater than strategy 2 mainly due to greater consumption of energy and chemicals. Also, it should be noted from Fig. 10(e) that unmet water demand in the BAU can be almost compensated steadily over the entire period only by strategy 1 due to greater water supply.

**Fig. 10.** Daily variations of the metrics for different strategies for (a) runoff (b) net GHG emissions (c) net acidification (d) net eutrophication, (e) water demand delivered, and (f) O&M cost.

Finally note that a more comprehensive decision support framework and tool can be further developed by linking the WaterMet$^2$ model to some decision support type methods (e.g. some Multi-Criteria Decision Analysis). For instance, a typical decision support framework can be used to simulate and analyse a variety of potential and complex intervention strategies by using WaterMet$^2$ and then rank them based on a number of performance criteria supported by either WaterMet$^2$ or other tools. As a result, a limited number of high ranked strategies can then be selected to be taken further to the next, detailed level of planning involving physically based simulation models. Hence, this process will assist stakeholders (e.g. water companies) in providing additional and detailed information and subsequently making more informed decisions.

## 5. Conclusions

The proposed methodology and associated software tool (WaterMet$^2$) was developed and presented here as a conceptual, mass balance based simulation model quantifying energy and other fluxes derived from the underlying water flows for a long-term planning horizon of an integrated UWS. The new methodology enables quantifying complex water-energy issues and associated impacts at different spatial and functional scales by linking together various urban water system (UWS) components and elements at 4 different spatial scales which, in turn, often results in complex water-energy feedback type loops being built and evaluated.  Furthermore, the main advantage of WaterMet$^2$ compared with the counterpart tools is in the assessment of the metabolism based performance of the UWS. This enables WaterMet$^2$ to concurrently quantify sustainability based metrics especially avoided and caused environmental impact categories (e.g. GHG emissions, acidification and eutrophication potentials) of the UWS in addition to various water flows and other business-as-usual impact categories (e.g. energy and cost). The WaterMet$^2$ methodology was demonstrated for strategic-level planning of the UWS of a northern European city. An aggregated model of the UWS was developed although the full capability of the model was not ideally demonstrated in this case study, due to the lack of detailed data required.

As demonstrated in a real-life case study shown, the required conceptual model can be relatively easily built and calibrated and then used for the long-term evaluation of different UWS configurations and associated system loads, both existing and modified (i.e. following some interventions). Based on the results obtained it can be concluded that the model can be used to effectively and efficiently quantify the UWS performance across the full urban water cycle. The model is particularly useful when the purpose is to measure impact of different configurations of the UWS on the long-term sustainability performance. For instance, applying the water recycling schemes would result in the overall improvement of the environmental impact categories although having a directly negative environmental impacts due to electricity consumption. Also, the WWTWs are accounted for the major sources of GHG emissions and acidification potential while causes of eutrophication potentials are shared mainly between WWTWs and sewer networks. This is likely the main cause that ‘water recycling’ strategy outperforms ‘addition of water resources' strategy with respect to environmental impact categories as the former strategy can impact on both sides of the UWS (i.e. water supply and wastewater/stormwater).

It should also be noted that one of the purposes for developing WaterMet$^2$ was to apply it to the cities where no physically based models exist or building such models is difficult (e.g. due to lack of access to the detailed required input data). This issue could be particularly a great concern for the case studies in developing countries in which the challenges may be quite different in terms of performance indicators (e.g. focus only on conventional indicators). In these cases, WaterMet$^2$ can still be applied to overcome these shortages and address those performance indicators of interest.

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# 8. Appendix I: Notation

## Glossary of terms used in this paper is as follows:

Black water (wastewater): resulted from those water consumptions (e.g. toilet and kitchen sink) which need a centralised treatment and are discharged into sewer systems.
Green water: treated rainwater which can be used for non-potable demands.
Grey water: dilute wastewater mainly originating from domestic consumptions (i.e. hand basin, washing machine, shower, dish washer) which can be used for non-potable consumptions with specific level of treatment. If not recycled, grey water will be added to the black water stream.
Groundwater: part of precipitation which is infiltrated into the ground through pervious areas.
Storm water: part of precipitation which is converted to runoff and can be discharged into sewer system.
Potable water: high quality water which meets drinking water standards.
Reuse/recycling water: treated greywater or green water which can be used for water demands.

## The following list of acronyms is used in this paper:

CSO: combined sewer overflow
DM: distribution main
DR: discharge route
GHG: greenhouse gas
GWR: greywater recycling
SC: subcatchment
(S/L)GWR: (subcatchment/local area) grey water recycling
SN: sewer network
SR: service reservoir
STO: storm tank overflow
(S/L)RWH: (subcatchment/local area) rainwater harvesting
TM: trunk main
RW: receiving water
RWH: rainwater harvesting
WR: water resource
WSC: water supply conduit
WTW: Water treatment works
WWTW: wastewater treatment works
UWS: urban water system