Quantitative UWS performance model: WaterMet²

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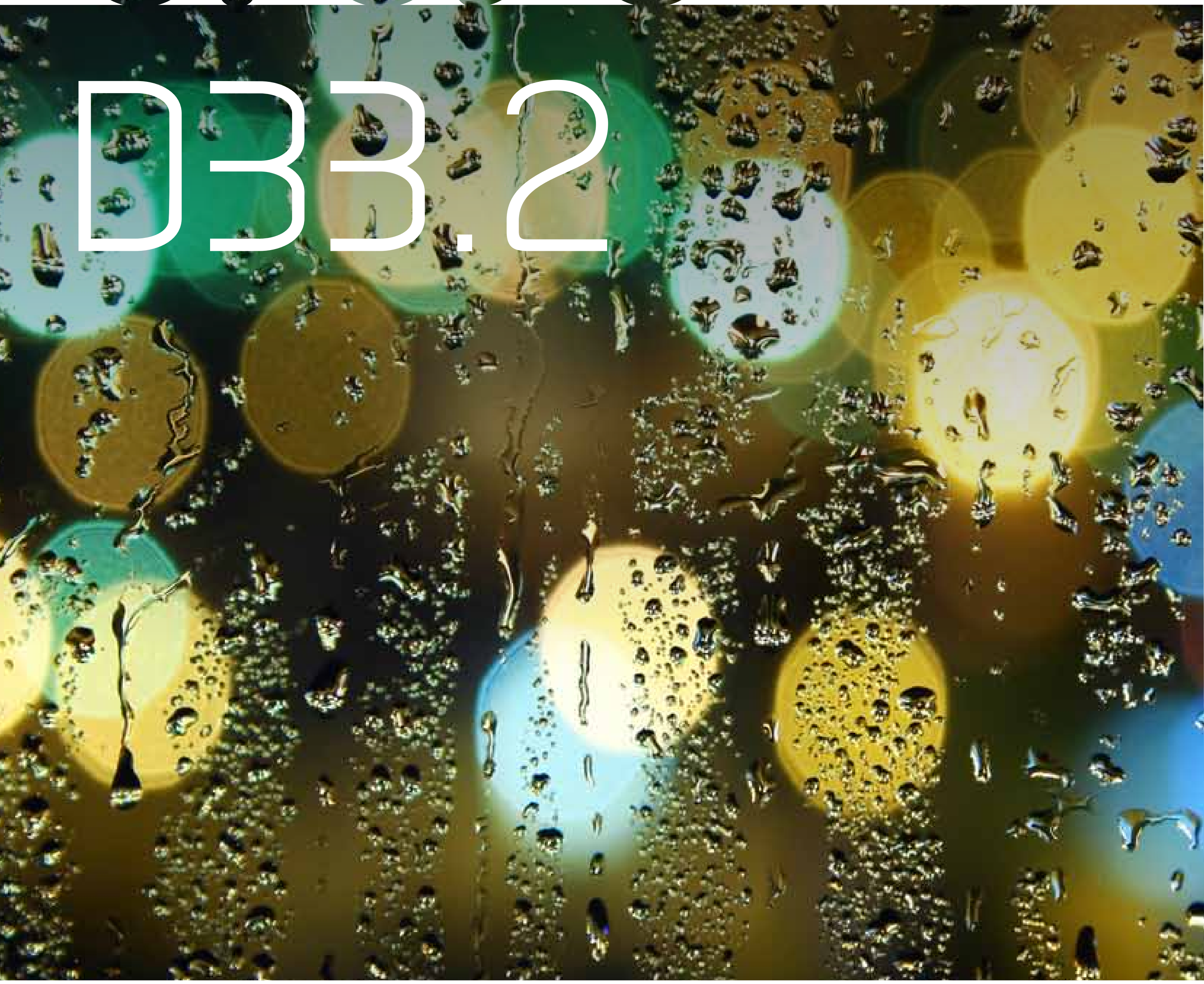

TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

QUANTITATIVE UWS PERFORMANCE MODEL: WATERMET^2

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ABSTRACT

The report presents a detailed description of the WaterMet^2 methodology and tool as a quantitative urban water system (UWS) performance model. The WaterMet^2 model is described in three distinct parts. Modelling concepts of different components in WaterMet^2 are first described. It provides an overview of the principle flows/fluxes modelled in spatial and temporal scales in WaterMet^2 and how they are modelled within the framework of mass balance equations in four subsystems (water supply, sub-catchment, wastewater and water resource recovery). The second part describes the WaterMet^2 software. This consists of an overview of WaterMet^2 on how input data are prepared, how to run a simulation and finally how to retrieve results in different formats. This part also introduces the WaterMet^2 toolkit functions which can be used by other programming languages to call a WaterMet^2 simulation model. In the third part, WaterMet^2 is illustrated using the city of Oslo UWS as a generic reference model. This part first describes building and calibrating a WaterMet^2 model for the existing UWS which faces water scarcity problems for a 30-year planning horizon starting from year 2011. Then, it examines two alternative intervention options (i.e. adding new water resource and water treatment options) which are supported by the WaterMet^2. These options are examined for the UWS model and the improvements are compared to the business-as-usual case.

1. Introduction

This report presents a detailed description of the WaterMet^2 methodology and software tool (note: 'Met' stands for both metabolism and metropolitan hence '^{2}'). WaterMet^2 is a quantitative urban water system (UWS) performance model developed as an analysis tool in the TRUST project for the long-term, strategic assessment of UWS performance and related planning under existing and a range of possible future scenarios. This report is a TRUST project deliverable D33.2 as one of the outcomes of work done in WP33 and WP34. The report has been prepared based on the earlier recommendations made in the Scoping Report (Brattebø *et al.* 2011), the relevant risk modelling concepts provided by the SINTEF (Ugarelli et al, 2014), the Functional Requirements Report (Behzadian *et al.* 2012), WaterMet^2 conceptual model report (Behzadian *et al.* 2013) and the Oslo Case Study Report (Behzadian and Kapelan 2012).

The WaterMet^2 model is developed in WP33 as a stand-alone software tool however it will be used as a piece of code for other deliverables in the TRUST project. More specifically, the WaterMet^2 model will become part of the decision support system (DSS) for the long-term planning of UWS in WP54. In the DSS, the WaterMet^2 model is used as a simulation model to support the assessment of intervention strategies in an UWS. Also the Toolkit functions of WaterMet^2 model will be used for the development of risk assessment models in WP32. Generally, the WaterMet^2 toolkit functions can be used for other analyses in other programming languages.

This report also presents the application of the WaterMet^2 model in the Oslo case study. More specifically, using the city of Oslo here as a reference city model combined with assumptions, when required, this report aims at explaining how the TRUST metabolism methodology can be applied by the user. The performance indicators of the UWS will be then calculated by using the WaterMet^2 model for a 30-year planning horizon starting from year 2011.

The report is organised as follows: (1) the first part outlines and describes the methodology of the WaterMet^2 model in which the key concepts behind the modelling approach used in the WaterMet^2 tool and the modelling of different components and processes in WaterMet^2 are explained; (2) in the second part, the WaterMet^2 model elements including input parameters and output variables are described in detail; (3) in the third part, modelling of the UWS in WaterMet^2 is demonstrated in a case study of the TRUST project.

2. Background

Urban metabolism studies deal with the quantification of the overall fluxes of energy, water, materials, nutrients and wastes into and out of an urban region (Wolman, 1965). The concept was originally developed in the mid-1960s in response to deteriorating air and water quality. 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). An UWS is system with a major contribution to the urban metabolism and is assessed by some sustainability performance measures. The sustainability performance indicators in the UWS have evolved over time from being primarily focused on safe drinking water, just a century ago, to multipurpose economic development, 50 years ago, to goals that now include environmental and ecosystem restoration and protection along with aesthetic and recreational aspects (ASCE, 1998). These indicators are affected by some external drivers due mainly to population growth, urbanisation, climate change and aging infrastructures; which may decrease the capacity and quality of services (Savic *et al.* 2013).

The UWS generally consists of three separate subsystems including water supply, storm water and wastewater collection. The traditional approach for modelling the UWS components/subsystems is to use physically-based models to separately analyse the behaviour of a number of interconnected components. These physically-based models are typically sophisticated and demand a substantial quantity of input data, while the output of the analysis addresses only part of the system. However, water companies wish to determine the overall performance of the entire UWS including water supply and wastewater components and aim to achieve technically and economically acceptable levels of service. Such physically-based models may not easily assess the impact of any changes in a component on the whole systems in an integrated and systematic way. These can be considered as a drawback when one considers the growing need for holistic, sustainable management approaches. Sustainability and decarbonisation are also often on the agenda; overburdening of the existing infrastructure is sought to be avoided. This aim can be realised within a simplified and integrated UWS model which needs lower data requirements to speed up wide scale modelling approach. This approach can form a conceptually based model with the ability of quantifying metabolism fluxes in an UWS (Venkatesh and Brattebø, 2011).

Modelling the urban water cycle has been of interest for many decades now (Graham, 1976; Rozos *et al.*, 2010). A surge in interest has been 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. These models, which represent a more holistic framework for the evaluation of urban water systems and enable 'what-if' type scenario modelling, have increasingly been employed by water professionals (Binder *et al.* 1997; Mitchell *et al.* 2002). A brief review of these recently-developed models is presented in the following.

The *Aquacycle* model which includes a new water balance model was initially developed in 2000, and further modified in 2002 and 2006, called *UVQ* (Urban Volume and Quality), (Mitchell and Diaper, 2006). It focuses on water flows and contaminant balance through the urban water supply, storm water, and wastewater subsystems and the interactions between them (Mitchell and Diaper, 2004; Mitchell *et al.*, 2001). The principal advantage of *UVQ* at that time was the ability to track waterborne contaminants and their flows for alternative water service provisions (Mitchell and Diaper, 2004).

A decision support tool called *UWOT* (Urban Water Optioneering Tool) was developed based on a water balance model to facilitate the selection of combinations of water-saving technologies as sustainable water management options (Makropoulos *et al.*, 2008). *UWOT* was subsequently upgraded to optimise the components of the water recycling schemes with an emphasis on rainwater harvesting and grey water recycling (Rozos *et al.*, 2010). In the most recently developed version, *UWOT* has been further extended to optimise the operation of a complex water supply subsystem including multi-reservoir systems (Rozos and Makropoulos, 2013).

A scoping tool called *CWB* (City Water Balance) was introduced for the rapid assessment of urban water management strategies (Mackay and Last, 2010). This tool was derived from the previously-developed models such as Aquacycle and *UVQ* (relative to spatial resolution) and *UWOT* (relative to indoor demand profile) and attempted to overcome some of drawbacks which become apparent in the applicability of those models.

Despite the substantial recent progress in the development of water management tools to broaden the scope to include all water-related aspects of the UWS, none of them was considered a truly holistic approach to integrated urban water management in which the impact of the key components on all others in the UWS can be evaluated. For instance, potable water is modelled in these tools as an external supply in *CWB* (Mackay and Last, 2010), supplied by a water service provider in UWOT (Makropoulos *et al.*, 2008) or as input data at a household scale in *UVQ* (Mitchell and Diaper, 2010). Despite *CWB* assuming fixed cost, energy and contaminant data for potable water, this approach is unable to assess the impact of subsequent interventions in the water supply subsystem. Similarly, the impact of an intervention implemented in the water supply subsystem cannot be assessed in the downstream side of the subsystem. On the other hand, Rozos and Makropoulos (2013) and Roozbahani *et al.* (2013) have only focused on the water supply subsystem side and the relevant interventions in their own conceptually-based models.

Therefore, there are some important issues which need to be addressed:

(1) Low data requirement;
(2) Sustainability performance indicators;
(3) Inclusion of key components of the UWS.

The first can be captured by conceptually based model outlined above. The second is 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). For the third issue, it is noted that the previously-developed conceptual models either consider the modelling between water demand point (starting with potable water from the point where it is delivered) and wastewater subsystems (Mackay and Last, 2010; Makropoulos *et al.*, 2008; Mitchell and Diaper, 2010; Mitchell *et al.*, 2001) or focus only on water supply subsystems between water resource and water demand points (Roozbahani *et al.*, 2013; Rozos and Makropoulos, 2013).

Furthermore, the focus of all of the aforementioned models is mainly based on the quantification of water flows and their final destinations in different parts of the UWS. However, the metabolism-related performance indicators employed in this research aim to quantify water flows plus other main fluxes of sustainability-related issues such as all types of direct and indirect (embodied) energy, material flows and greenhouse gas emissions resulting from the entire urban water cycle.

Further, this research strives to extend the metabolism-based modelling concept and to create an integrated model (i.e. WaterMet^2) of an UWS including the key components in water supply, water demand, sewerage and drainage subsystems - building upon the concepts but extending the methods applied in a previous analysis of the Oslo city (Venkatesh and Brattebø, 2011).

WaterMet^2 is developed as a standalone piece of software written by programming language of C# under Microsoft Visual Studio .Net Framework which runs in a Windows™ screen with the capability of navigational devices to build a new UWS model.

Compared to WaterMet^2, another metabolism model called DMM (Dynamic metabolism model) is developed in TRUST project (Venkatesh *et al.* 2012). DMM is an integrated UWS, user-friendly and MS Excel-based model which can be easily populated. It calculates some KPIs of the UWS for a specific point in time which would be either for today and in the long run for given scenarios. This enables water utilities to compare the KPIs over time to gauge improvements, or also to compare the performance of different utilities. The DMM model also calculates the resources (e.g. chemicals and materials) required for running the water and wastewater subsystems. It can be used for the entire city or sub-catchments, but there is no connection between the sub-catchments and there is no time step. Consequently, a principal difference between WaterMet^2 and DMM is the need for spatial and temporal resolutions. More specifically, while DMM is temporally static and spatially aggregates the whole water consumption points, WaterMet^2 simulates the performance of the UWS over a long-term time period with a daily time step and is able to disaggregate water consumption points into a number of different parts. The detailed description of WaterMet^2 methodology will be presented in the next chapter.

3. WaterMet^2 Methodology

3.1. WaterMet^2 modelling concept

The WaterMet^2 model is a simulation, mass-balance-based model which quantifies the metabolism[1] related performance of the integrated UWS with focus on sustainability-related issues. The integrated modelling of the UWS implies the whole processes and components in an urban area related to water flows as a complex and interrelated system. More specifically, the WaterMet^2 model calculates the principal water-related flows as well as all other system fluxes (e.g. energy, greenhouse gas emissions, chemicals and materials) sequentially in the UWS. All this, in turn, will enable calculating a number of different indicators such as the total amount of water supplied, energy used, greenhouse gases emitted, operational and maintenance costs, any risk and intervention assessment for any component or the whole system over some pre-defined planning horizon. The WaterMet^2 model quantifies aspects of both water quantity and quality modelling. 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. The WaterMet^2 model is generally developed as a generic UWS for the application to any city through the TRUST project partners although it is first applied and tested for Oslo case study which will be described in chapter 5.

Figure 3 1 illustrates the main flows and storages modelled in the WaterMet^2, which comprises four main subsystems. A mass balance approach of water is followed within the system. The water sources and sinks are the water boundaries which supply and receive water, respectively. The water storages stand for any physical assets storing water in which some water related processes may take place. The storages are interrelated to each other through a variety of defined water flows. The water flows represent any physical assets conveying water flows between different water storages in the UWS. The model recognises various types of water streams, each of which demands special attention for storage and treatment and can only be allocated for particular water consumptions. The user needs to specify the relevant parameters of all water flows and storages. An overview of spatial and temporal representations of the UWS is presented in the next sections followed by a brief description of principal WaterMet^2 fluxes. More detailed description of WaterMet^2 modelling concept can be found in Behzadian *et al.* (2012).

[1] metabolism in UWS is referred to the flows and conversion processes of all kinds of water flows, materials and energy in UWS to fulfil the necessary functions

3.1.1. Spatial UWS Representation

WaterMet^2 adopts the administrative limits of an urban water utility as the spatial limit of the UWS. It also recognises the following four spatial scales representing the whole UWS: (1) indoor area; (2) local area; (3) sub-catchment area; (4) city area.

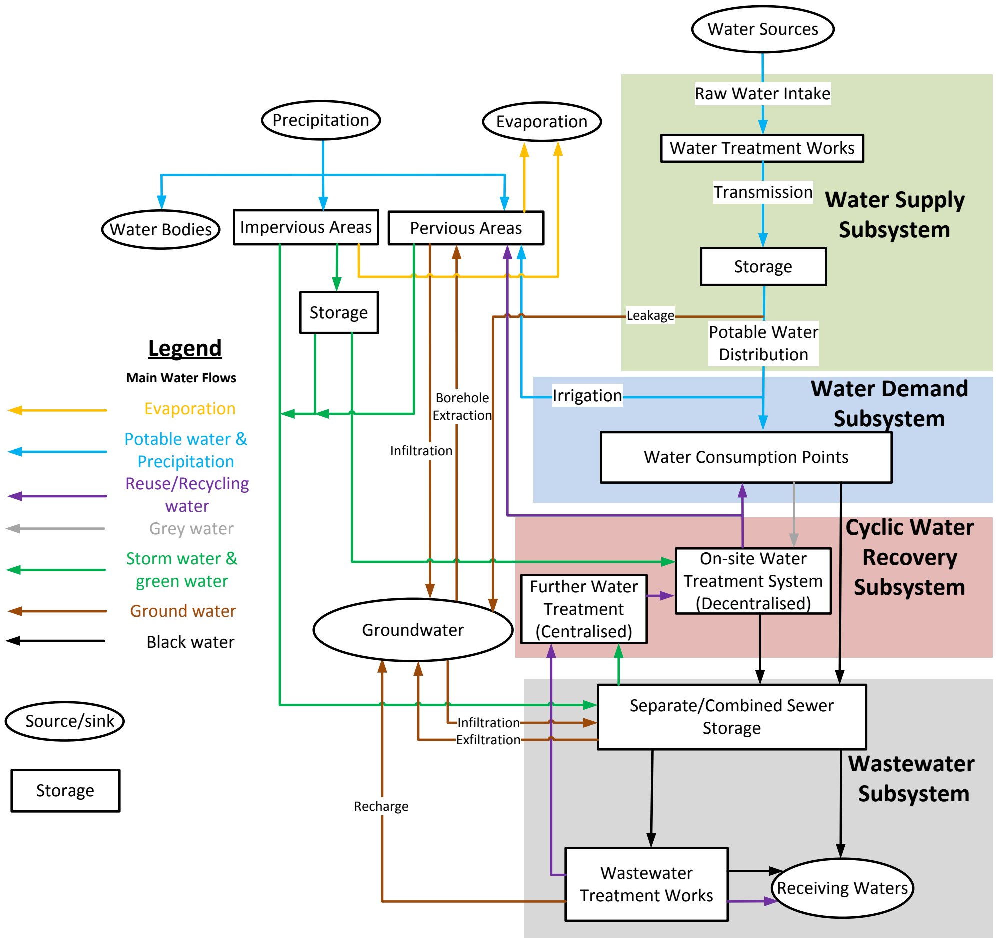


Figure 3 1: Main flows and storages in the WaterMet^2 model

Indoor Area Scale

The smallest spatial scale of the UWS in the WaterMet^2 model is an indoor area. It is used to represent a single household or property (e.g. residential, industrial, commercial, public, etc.) without any surroundings (e.g. garden or public open space representing any outdoor area). Indoor water consumptions in the WaterMet^2 model are defined at this level.

Local Area Scale

A group of similar typical households/properties with a surrounding area in the WaterMet^2 is represented as a local area. It can contain any number of indoor areas (i.e. properties) but they all must be of the same type, i.e. with identical per capita water demand. The surrounding area is divided into pervious surfaces, impervious surfaces and water bodies (e.g. lake and river). The main tasks of local area in WaterMet^2 are to handle outdoor water demands, rainfall-runoff modelling and on-site water treatment options which are discussed in sections 3.2.2, 3.2.3 and 3.2.4, respectively. The main physical components modelled by WaterMet^2 only on this level are on-site water treatment options on the scale of local area (i.e. rainwater harvesting and grey water recycling schemes).

Figure 3 2 represents a schematic diagram of an example urban area with several groups of similar households/properties and the surrounding areas. For the purpose of WaterMet^2 modelling, this urban area can be represented using a number of local areas as: (1) three residential local areas, each with a different type of house (e.g. detached, terraced and flat) modelled. The surrounding area for these cases may be private gardens and a shared part of public pavement and road around the households; (2) the local area representing an institutional block and the surrounding area including private and public gardens.; (3) the local area representing the commercial area with similar commercial properties (i.e. indoor areas) and the associated surrounding land.

Note that the above example presents a detailed (i.e. accurate) spatial representation of the relatively small urban area analysed. However, when covering larger urban/city areas in the WaterMet^2 model, the same approach outlined above can be used but it would typically involve larger individual local areas, each comprised of a larger number of 'typical' properties (i.e. indoor areas), e.g. a large residential block comprised of similar apartments (or houses) with the associated surrounding area. Therefore, a local area can be used to represent a relatively large (or small) spatial area depending on the size/type of the urban area analysed but also on the level of spatial resolution required (which is typically a function of the objectives of the study undertaken).

Figure 3 2: Schematic diagram of a zone in a city with different types of local areas

Subcatchment Area Scale

A subcatchment area is used in the WaterMet^2 model to represent a group of neighbouring local areas. Each subcatchment area represents a storm water /wastewater subsystem, i.e. 'collection point' in a separate/combined sewer system with associated water demand supplied by the potable water distribution network. Two main physical components particularly defined on this level are: (1) Rainwater harvesting tank on subcatchment scale; (2) Grey water recycling tank on subcatchment scale.

To give an example, Figure 3 3 shows a schematic diagram of a city area that can be basically divided into two individual catchments in the north and the south (Figure 3 4) based on the different topographies for storm drainage. These two catchments can be further divided into a number of subcatchments representing drinking water consumption points in the water distribution network. In addition, they represent separate wastewater /storm water collection points for the centralised sewer system. Consequently, the city area in this example can be composed of 14 subcatchments including 8 subcatchments (A through H) in the northern part and 6 subcatchments (I through N) in the southern part.

Figure 3 3: Schematic diagram of a city area modelled by WaterMet^2 (photo taken from CPLA 2004)

The subcatchment areas are defined by the user mainly based on the considerations of topology and the gravity of storm water/wastewater collection systems. The subcatchment area can represent relatively large (or small) spatial areas depending on the city area size, the level of spatial resolution required and the available data for different subcatchments and the associated local areas. For instance, if there is a lack of available data for defining a variety of subcatchments in a city area, one can consider the city 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 such as frequency and duration of CSOs, pollutant graphs, energy and GHG fluxes, related operational and maintenance costs, etc. In addition, modelling city area using a small number of subcatchment areas will also reduce the spatial resolution required for modelling different interventions. Therefore, a trade-off exists between the spatial and other level of detail modelled and the accuracy and usefulness of the WaterMet^2 model built.

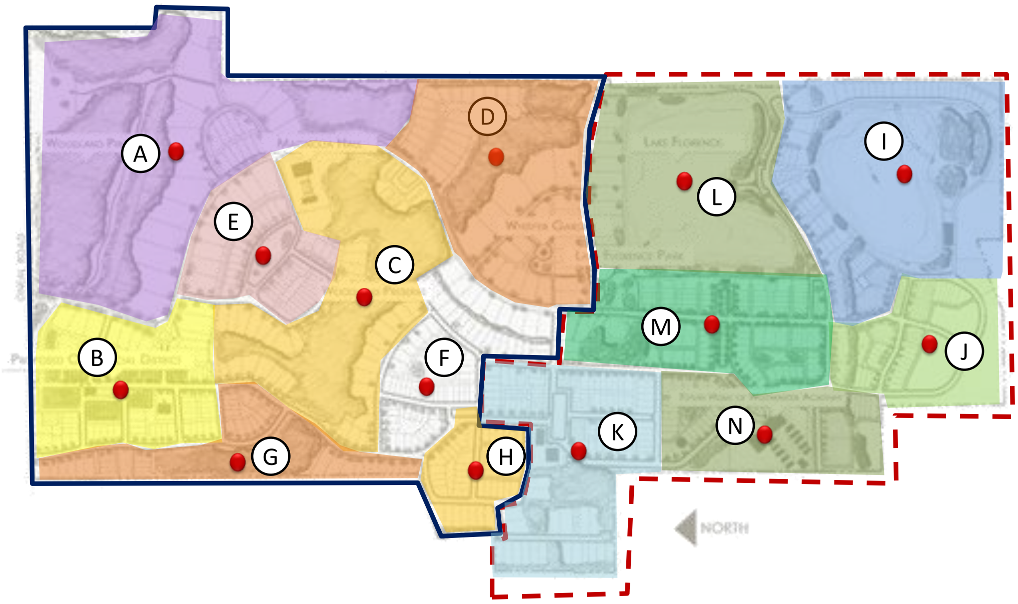


Figure 3 4: Schematic diagram of subcatchments in a city area

Furthermore, a representation of spatial distribution of neighbouring local areas for each subcatchment of the above example as previously discussed can be shown in Figure 3 5. For instance, Subcatchment C can be divided into two different local areas and Subcatchment F can also be divided into three. In addition, spatial distribution of neighbouring local areas for a subcatchment of the previously discussed example (Figure 3 2) can be represented in Figure 3 6. Here, five different local areas (A through E) are defined in the subcatchment based on the methodology outlined above. As described earlier, the number of local areas modelled in each subcatchment can be small or large, depending on the level of accuracy required and the data available. Note that a subcatchment is populated by a number of pre-defined 'typical' local areas for each of which the number of indoors/properties and total area are specified. Also, when defining each 'typical' local area, unique water consumptions for indoor area and unique outdoor specifications (e.g. percentages of pervious, impervious area and so on) are determined for the respective 'typical' local area. In addition, the sum of wastewater/storm water collected from different inside local areas in a subcatchment is delivered to sewer system and represented as wastewater/storm water of the relevant subcatchment.

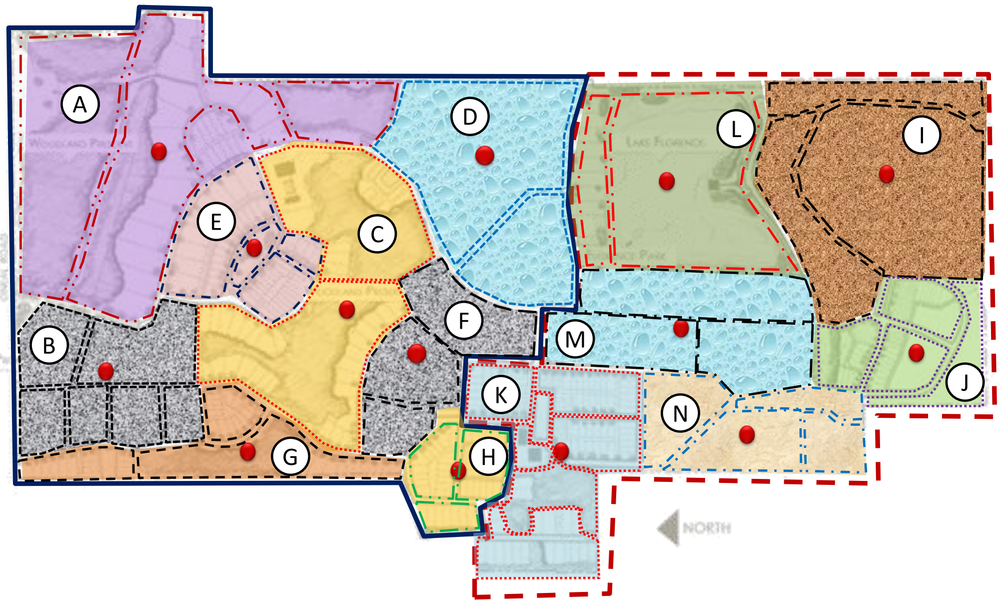


Figure 3 5: Schematic diagram of local areas in different subcatchments

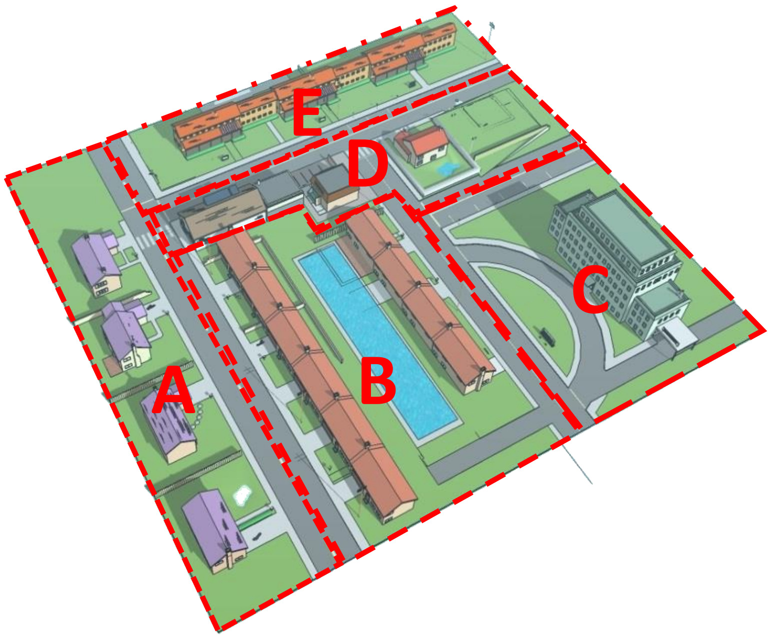


Figure 3 6: An example of partitioning a subcatchment area into a number of local areas

City Area Scale

The main components of an UWS are represented on the city scale as the top level of the WaterMet^2 modelling resolution. The principal flows and storages modelled on this level are represented in Figure 3 7. The following main components are defined and modelled only at this level, which will be described in more details in sections 3.2.1, 3.2.3 and 3.4:

- Water resources;
- Water Supply Conduits;
- WTWs;
- Trunk mains;
- Service reservoirs;
- Distribution mains;
- Subcatchments;
- Separate/combined sewer systems;
- WWTWs;
- Receiving waters;

Other than defining any number of the aforementioned UWS components in WaterMet^2, the city area in the WaterMet^2 model can be divided into any number of different subcatchments. This number highly depends on the available data and the level of interventions to be assessed.

A brief list of all the processes and components modelled at different spatial levels of the WaterMet^2 are summarised in Table 3 1.

Table 3 1: Components modelled at different spatial levels in WaterMet²

SPATIAL LEVEL IN THE WATERMET² MODEL		INDOOR AREA	LOCAL AREA	SUBCATCHMENT AREA	CITY AREA
Component	Description				
Water Consumption Points	including Indoor and Outdoor water usages	✓	✓		
Rainwater Harvesting Tank	collection and treatment of rainwater from impervious areas for water reuse		✓	✓	
Grey Water Recycling Tank	collection and treatment of grey water from water consumption points for water reuse		✓	✓	
Water Supply Conduits	conveyance of raw water from Water Resources to WTWs				✓
Trunk Mains	conveyance of potable water from WTWs to Service Reservoirs				✓
Distribution Mains	distribution of potable water from Service Reservoirs between water consumptions				✓
Combined/Separate Sewer Systems	collection of sanitary sewage/ storm water runoff from subcatchment area and conveyance to WWTWs				✓
WTWs, WWTWs	treatment of raw water and wastewater				✓
Service Reservoirs	potable water storage prior to distributing between the costumers				✓
Water Resources	raw water sources for WTWs				✓

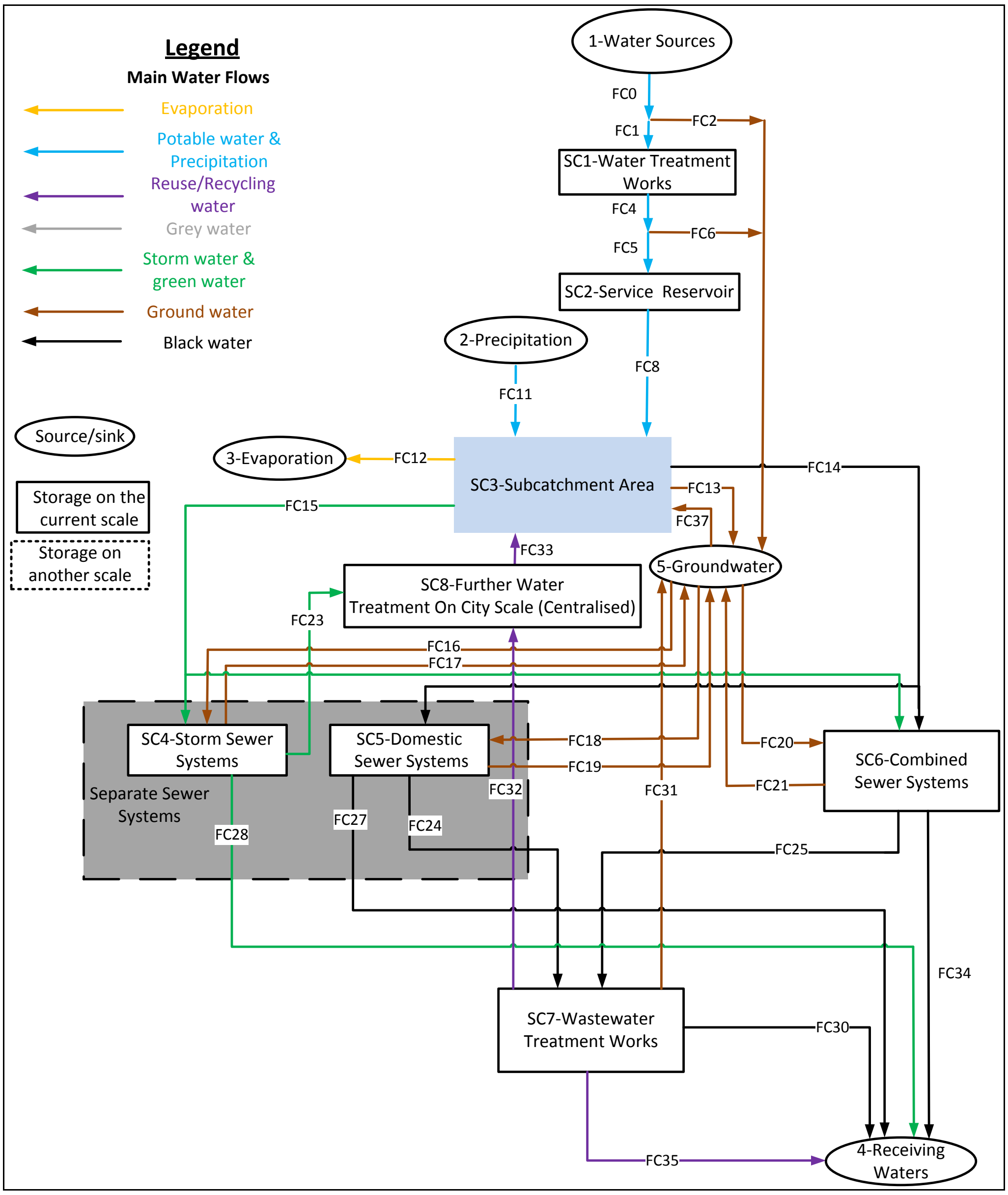


Figure 3 7: Water flows and storages on city area level in WaterMet²

3.1.2. UWS Temporal Discretization

The metabolism WaterMet² model aims to support strategic planning, hence a daily time step is selected as the default and smallest temporal scale. The WaterMet² model will use the daily time step to simulate the UWS performance for a period of N years which is specified by the user. Consequently, all the time series required in the WaterMet² model such as weather data and inflow to water resources need to be provided as a daily basis for the entire time period being analysed. A minimum of one year is envisaged to take into account any seasonal variations of water demands but longer simulation durations spreading across multiple years are more likely/ desirable.

3.1.3. Principal WaterMet^2 Flows/Fluxes

The key performance indicators (KPIs) of the UWS are calculated through the main WaterMet^2 fluxes. The principal flows/fluxes analysed in the components of the UWS WaterMet^2 model are: (1) water flow, (2) energy flow; (3) greenhouse gas emission (GHG) flow; (4) pipeline material flux; (5) chemical flux; (6) pollutant flux. These flows are modelled and calculated whenever generated, consumed and replaced and they can be aggregated temporally and spatially within components, subsystems and the city area. A brief overview of these flows/fluxes is outlined below.

Water Flow

The WaterMet^2 model simulates the main streams of water flow (Makropoulos *et al.* 2008) including clean (potable) water, storm water, grey water, green water, recycling (reuse) water, wastewater (black water). **Potable water** refers to the treated water in WTWs, originally supplied from water resources. **Storm water** is the rainfall on both impervious and pervious areas. **Green water** denotes the treated rainwater modelled in local area scale. Grey water is the dilute wastewater flows originating from some clean water consumption. Specifically, WaterMet^2 assumes shower, hand basin, dishwasher and washing machine as the potential appliances and fittings for producing grey water. Grey water typically contains some organic and inorganic materials (e.g. detergents), sand and salt which can be reused for specific consumption immediately after some primary treatment (Balkema, 2003). **Black water** is the used wastewater obtained from toilet and polluted water consumed by industrial/commercial users which need to be collected and treated at WWTWs. **Recycling water** is used to describe return water treated by water treatment options by either centralised (i.e. WWTWs) or decentralised (i.e. grey water recycling schemes at either local area or subcatchment level). Note that if no grey water recycling scheme is activated at the local area in WaterMet^2, all water used is converted to black water and no grey water is generated.

Water flows in WaterMet^2 are comprised of two parts, water quantity and water quality. Water quantity modelling encompasses within all subsystems while water quality modelling is only included within wastewater and cyclic water recovery subsystems. The principles of this modelling will be described in the following sections in more detail.

Energy Flow

WaterMet^2 calculates the energy consumed for each component of the UWS such as energy required for raw water transmission to WTWs, operation of WTWs, WWTWs and on-site water treatment options. Three sources of energy are taken into account by the WaterMet^2 model including (1) fossil fuel, (2) electricity drawn from the grid and (3) embodied energy resulting from materials used for each component such as chemicals used in WTWs and WWTWs and pipeline rehabilitation in water distribution and sewer systems. All these three types of energy are calculated by multiplying the amount of consumption by a conversion coefficient for that specific source of energy. WaterMet^2 employs a database for a number of energy sources, materials, chemicals and by-product which is given in Appendix A. In addition, the WaterMet^2 model calculates other heat and energy generated within the UWS as resource recovery. They include (1) electricity generated in water distribution network by micro-turbines, (2) heat and electricity generated in WWTWs by biogas, anaerobic digestion, turbine-generator and (3) heat generated from WWTWs effluents by heat pump.

Greenhouse Gas Emission (GHG) Flow

The WaterMet^2 model calculates GHG emission in three different ways: (1) those emitted directly from fossil fuel consumption in the components such as water pumping, WTWs and WWTWs to the atmosphere; (2) those emitted indirectly from electricity consumption in the components such as water pumping, WTWs, water treatment facilities and WWTWs to the atmosphere; (3) those emitted indirectly from material flux (resulted from embodied energy of materials) such as the pipeline rehabilitation in water supply and sewer systems and chemicals used for treatment processes. Contribution of GHG emission is reported in kg of CO_2 emissions equivalent. This is because the main sources of energy flows in UWS (i.e. fossil fuel combustion used for electricity generation, motor transport and pipeline production) contribute mainly in CO_2 emissions as a main GHG emission. The aforementioned GHG emissions are calculated by multiplying the amount of energy, chemical and material consumed by a conversion coefficient for that specific energy, chemical and material. This conversion coefficient is expressed as kg of CO_2 equivalent per consumption unit and is specific for different energy types, chemicals and materials. The database of these conversion coefficients for a number of materials, chemicals, energy sources and by-product used by WaterMet^2 is given in Appendix A. Note that all types of energy recovery (e.g. renewable energies) outlined above does not emit any GHG emissions and thus is excluded from the calculation of GHG emissions.

Acidification/Eutrophication Flow

The WaterMet^2 model also tracks down acidification and eutrophication for all types of GHG emissions outlined above. Similarly, these flows are calculated as daily basis by multiplying the amount of energy, chemicals and materials consumed by a conversion coefficient. The conversion coefficient is expressed as kg of SO_2-equivalent (acidification) and PO_4-equivalent (eutrophication) per consumption unit of that specific energy, chemical and material. Similar to the previous parts, the database of acidification and eutrophication for a number of materials, chemicals, energy sources and by-products used by WaterMet^2 is given in Appendix A.

Pipeline Material Flux

The WaterMet^2 model calculates the annual fluxes of materials used in the UWS over the analysed planning horizon. These material fluxes are linked to urban water system assets and their characteristics with focus on the water distribution and sewer pipelines.

Any changes in the quantity of urban water system assets (e.g. pipe lengths) due to interventions (e.g. addition of new pipes, rehabilitation and/or removal of existing pipes, etc.) or simply aging (i.e. 'doing nothing') are tracked down over the planning horizon. The assets analysed are categorised using their several key characteristics (e.g. pipe material, diameter, age, etc.). This enables to first quantify the impact of aforementioned interventions on asset quantities and their key characteristics modelled and then, in turn, the further impact of this on the associated material fluxes and system performance. Note that the latter may require using some simple lookup curves/tables/equations linking one or more key asset characteristics to the analysed performance indicator (e.g. leakage).

Finally, the tracked-down assets and associated material fluxes are used to calculate the embodied energy and related GHG emissions associated with the life cycle of the pipelines, including asset manufacturing, installation, operation/maintenance, rehabilitation and retirement (Venkatesh *et al.* 2009).

Chemical Flux

The WaterMet^2 model calculates the flux of individual chemicals used in different UWS components (i.e. WTWs, WWTWs and service reservoirs). The chemicals modelled in WaterMet^2 are: Alum, $Ca(OH)_2$ (calcium hydroxide), Carbon dioxide, Microsand, PAX (polyaluminium chloride) and NaOCl (sodium hypochlorite), all consumed in WTWs; chlorine consumed for disinfection in service reservoirs; and $FeCl_3$ (ferric chloride) $Fe_2(SO_4)_3$ (ferric sulphate) PAX, $Ca(OH)_2$, Ethanol, Methanol, Nitric acid, all consumed in WWTWs.

Pollutant Flux

The WaterMet^2 model calculates and tracks down the flux of pollutants (e.g. biological oxygen demand or BOD, total suspended solids or TSS, Tot-P (total phosphorus), Tot-N (total nitrogen)) in different parts of wastewater and cyclic water recovery subsystems once they are generated/ removed. In addition, the sludge generated from pollutant removal is also calculated in the UWS. The flux of pollutants is tracked down until they are discharged into receiving water bodies in the UWS.

3.2. Modelling of UWS components in WaterMet^2

3.2.1. Water Supply Subsystem

The WaterMet^2 model adopts a simplified approach for the water supply subsystem in which 'source to tap' modelling is performed. The elements modelled in the water supply subsystem are: 1-three 'storage' components including raw water resources, WTWs and service reservoirs; 2-three principal flow 'routes' including water supply conduits, trunk mains and distribution mains; 3-subcatchments as water consumption points. Figure 3 8 and Figure 3 9 show an example of the layout of the main components and the hierarchy of all types of component in a water supply subsystem, respectively. For instance in Figure 3 8, Resource1 supplies raw water through Water Supply Conduit1 (SC1) for WTW1 feeding Service Reservoirs 3 and 4 through Trunk Mains 1 (TM1) and 2 (TM2). Drinking water can be supplied from more than one Service Reservoirs. For instance, drinking water of subcatchment M is supplied from Service Reservoirs 3 and 4 through Distribution Mains 18 (DM18) and 14 (DM14) respectively or subcatchment E is fed by Service Reservoirs 1 and 2 through Distribution Mains 2 (DM2) and 5 (DM5) respectively. Note that there is no further modelling for the drinking water supply subsystem inside each subcatchment where drinking water is automatically allocated between different water consumers of local areas located inside each subcatchment. Note that in some water supply subsystems, there are no trunk mains or service reservoirs. Instead, treated water is directly distributed between customers through distribution mains. In such cases, unlimited capacity needs to be specified for dummy trunk mains and service reservoirs.

Simulation of the water supply subsystem in WaterMet^2 is carried out in two steps. The first step deals with the calculation of daily water demand starting from the most downstream points (i.e. subcatchments) and aggregating in the upstream direction until it reaches the most upstream points (i.e. water resources). Through this procedure, the calculated water demand in the components may be limited by the capacity of the relevant components. Further details of this type of control will be explained in the following sections.

Having determined water demand for each water resource, the second step starts with distributing water flow in the downstream direction. At the most upstream point, the water release (abstraction) is first supplied from each water resource providing there is enough storage in the water resource. The released/abstracted water is transferred to the downstream elements until it reaches eventually to subcatchments. This procedure is first started by transferring raw water to WTWs by water supply conduits. Then, treated water is transferred through trunk mains to service reservoirs within the urban area. Finally, potable water is spatially distributed between different subcatchments, i.e. each subcatchment is assumed to receive its share (i.e. percentage) of potable water from each of service reservoirs.

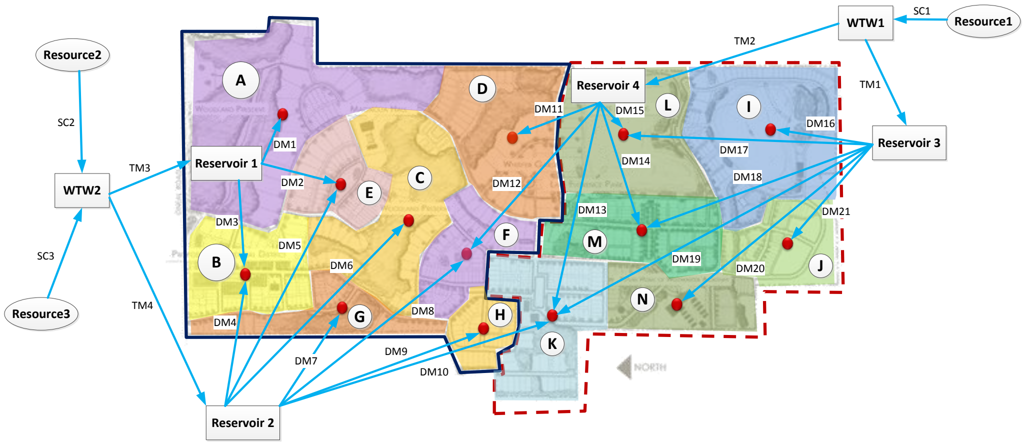


Figure 3 8: An example of water supply subsystem representation in WaterMet^2; SC=water supply conduit; TM=trunk main; DM=distribution main;

For calculating water demands in the first step and distributing water supply in the second step, water flow needs to be split especially if there are two or more flow routes. This can be performed by specifying an appropriate percentage split (i.e. water allocation share or coefficient) of flow for different routes. Generally, the percentage (or coefficient) for each flow route can be calculated based on one of the following methods:

(1) Pre-specified percentage coefficients of upstream routes connected to a 'storage' component.
(2) Pre-specified percentage coefficients of downstream routes connected to a 'storage' component.
(3) Proportional to flow capacity of upstream routes connected to a 'storage' component.
(4) Proportional to flow capacity of downstream routes connected to a 'storage' component.

The coefficients in the first two methods are defined by the user but, in the last two methods, they are specified automatically based on flow capacities. Note that methods 1 and 2 are compatible with the two-step simulation outlined above as these methods will provide the water allocation coefficients when calculating water demands in the upstream direction. Within the first step, new water allocation coefficients for distributing water in the downstream direction are calculated. However, methods 3 and 4 cannot be compatible with this type of simulation. Thus, WaterMet^2 accepts the first method for specifying these allocation coefficients between the flow routes. Therefore, the user needs to specify these coefficients for all three types of flow routes. To give an example in Figure 3 9, Subcatchment1 is supplied by two service reservoirs (Service Reservoirs 1 and 2) through two distribution mains (DM_1 and DM_2). For the case of allocation coefficient i_1 and i_2, in where

i_1+ i_2=100%, need to be specified by the user. Obviously, Subcatchment2 is only supplied by Service Reservoir3 through DM_3 and thus the allocation coefficient for DM_3 (i_3) is 100%. Generally, specifying the allocation coefficient of water flow is necessary wherever two or more flow routes supply one 'storage' component. The same rule will apply for trunk main routes (between WTWs and service reservoirs) and water supply conduits (between WTWs and water resources).

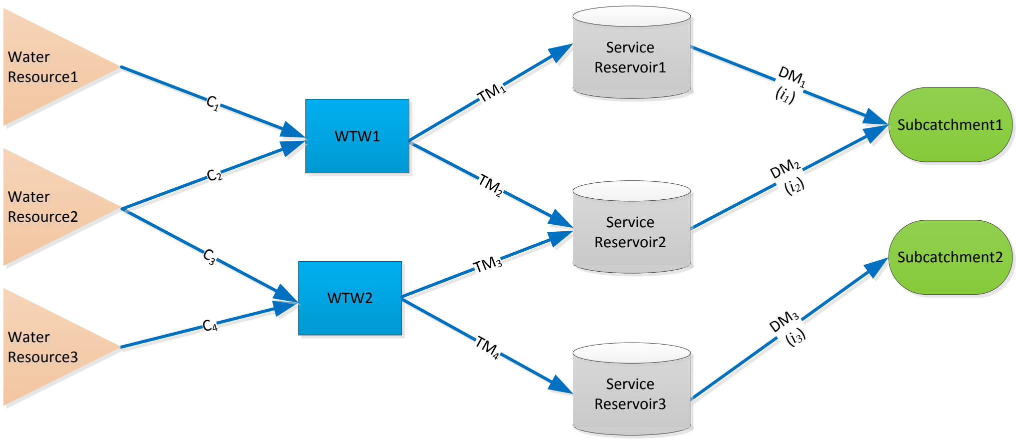


Figure 3 9: Hierarchy of water supply subsystem components in WaterMet²; Note that C=Water supply conduit, TM=trunk main, DM=Distribution main.

Modelling of water flow follows mass balance principles for each component. For storage components (e.g. dammed reservoir, service reservoir and treatment plants), the following mass balance relationship is applied to calculate the volume of the component for next day:

$$S_{i,t+1} = S_{i,t} + I_{i,t} - D_{i,t}$$

3-1

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. For such a component, the supplied water (Oi,t) is calculated based on the minimum storage volume of the component ($S_{i,min}$) as follows

$$O_{i,t} = \begin{cases} D_{i,t} & if\ \ S_{i,t+1} \geq S_{i,min} \\ S_{i,t} - S_{i,min} + I_{i,t} \quad \text{and} \quad S_{i,t+1} = S_{i,min} & if\ \ S_{i,t+1} < S_{i,min} \end{cases}$$

3-2

More details of mass balance principles for each type of UWS components are specifically discussed in the next section. Furthermore, along with mass balance type modelling of water flow within the UWS elements with a daily time step, other fluxes tracked down in the water supply subsystems are: (1) energy flow; (2) greenhouse gas emission (GHG) flow; (3) monetary flow and (4) chemical flux. All these flows are simply calculated in each time step based on the amount of the water conveyed/treated and the amount of that flux consumed per unit volume of water. The latter is specified for each element as input data of WaterMet^2.

Water Resources

The first and most upstream components in the water supply subsystem modelled in WaterMet^2 are water resources which provide raw water for WTWs through water supply conduits (see Figure 3 8, Figure 3 9 and Figure 3 10). WaterMet^2 recognises three types of resources including (1) surface water (e.g. lake, dammed reservoir, river); (2) groundwater and (3) desalination. Once water resources are defined, the user can choose the type of interest. Each of these types has its own requirements which are described in the following but some specifications are similar for all types. They include energy consumption (i.e. electricity and fossil fuel) per unit volume of water and O&M cost.

- **Surface water**: It refers to abstractions from any kind of surface water resources such river, lake or dammed reservoirs. This type of water resource uses Eqs. (3 1) and (3 2) to calculate the abstracted water from the resource. Therefore, it has specific storage and thus it is required of the user to define storage capacity, initial volume, annual water loss and time series of inflow. Note that initial volume is used for the first day of the simulation. Also, each surface water reservoir needs to have an individual time series of inflow with a daily basis covering the entire planning horizon.
- **Groundwater and Desalination**: They refer to abstraction of raw water from aquifers and acquisition of fresh water by desalinating the sea water, respectively. Note that WaterMet^2 considers no storage for this type of water resource and thus no storage capacity, water loss or time series of inflow needs to be provided.

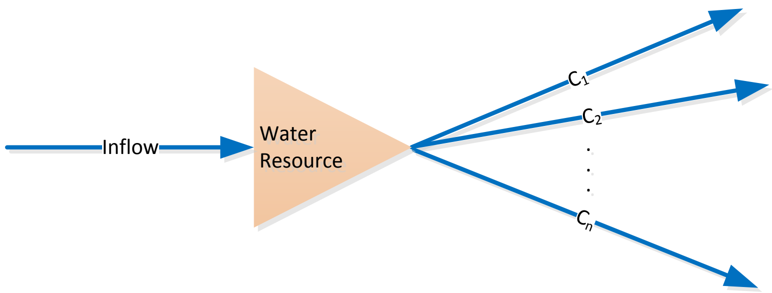


Figure 3 10: Schematic diagram of Water Resource and its connected routes modelled in WaterMet²; Note that inflow is only available for surface water

Water Supply Conduits

Water supply conduits are conveyance elements transmitting raw water from water resources to WTWs on a daily basis. Two main characteristics of water flow for each conduit are daily capacity and leakage percentage. Both values are defined by the user in WaterMet² as constant values. The daily capacity controls the maximum water flow transferred by the conduits. The leakage is based on a percentage of transferring water. If more than one conduit feeds a WTW, each conduit is responsible to provide a pre-specified fraction (i.e. percentage) of water demand for that WTW (CF_j). Once calculating the daily volume of water demand for each water resource ($RD_{i,t}$), the leakage volume related to each of the connected conduits ($CL_{j,t}$) is added to the water demand of that conduit ($WD_{j,t}$) as follows

$$RD_{i,t} = \sum_{j=1}^{n} CF_j \times WD_{j,t}\left(1 + CL_{j,t}\right) \quad j \in \text{WTWs and conduits connected to resource } i$$

3-3

If the calculated water demand transmitting from a particular conduit ($WD_{j,t}\times(1+CL_{j,t})$) exceeds the daily capacity of that conduit, a portion of water demand exceeding the conduit capacity ($CCap_j$) does not take into account for water demand of the upstream component and thus is counted as undelivered outflow from that conduit ($CUD_{j,t}$) as

$$CUD_{j,t} = CCap_j - WD_{j,t}\left(1 + CL_{j,t}\right)$$

3-4

Then, the leakage is deduced from the water transferred by conduits as soon as the water demand is distributed between the WTWs. Furthermore, the flows of energy (electricity or fossil fuel), GHG emissions, acidification, eutrophication and O&M cost are calculated based on the daily total volume of water transferred by each conduit (including leakage).

Water Treatment Works (WTW)

After transmitting raw water from water resources to WTWs, the treatment process is carried out in WTWs and treated water is transferred to service reservoirs (see Figure 3 9 and Figure 3 11). In the WaterMet^2 model, WTWs can be connected to any number of water resources and service reservoirs. The main characteristics of water flow in each WTW, defined by the user, are daily treatment capacity and water loss. The daily treatment capacity controls the maximum daily treatment and water loss takes into account the percentage of treated water which is removed from the water flow (e.g. evaporation or infiltration). The water demand and other flows (e.g. delivered and undelivered outflows) in each WTW are calculated similar to Conduits as described by Eqs. (3-3) and (3-4).

In the WaterMet^2 model, WTWs are analysed within two processes including physical and chemical. For each process, the flows of energy (electricity or fossil fuel), chemicals, GHG emissions, acidification, eutrophication and O&M cost are calculated as outlined previously. The chemical flow is calculated for each WTW by multiplying the volume of treated water by the amount of required chemicals per unit volume of water. Note that a library of existing chemicals is available for the user to specify the chemicals of interest for each WTW. The GHG emissions, acidification and eutrophication in WTWs are attributed to electricity, fossil fuel and chemicals used for water treatment. Operational costs for each WTW in WaterMet^2 include electricity, fossil fuel and fixed annual operational costs for both physical and chemical processes plus the average chemical cost.

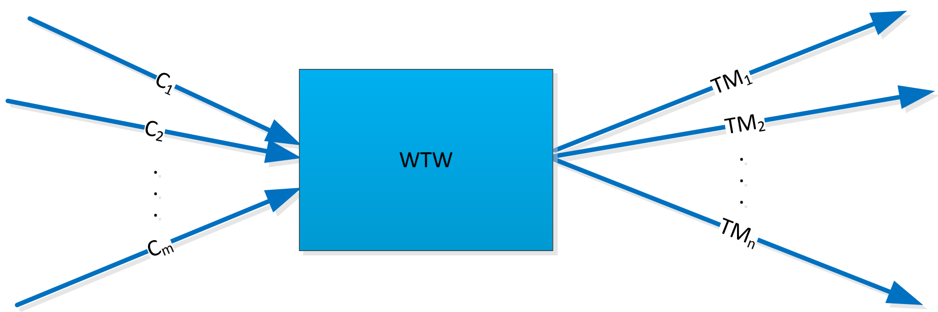


Figure 3 11: Schematic diagram of WTW and its connected routes modelled in WaterMet^2

Trunk Mains

Treated water in WTWs is transferred to service reservoirs by trunk mains (see Figure 3 9 and Figure 3 11). The functionality of trunk mains is the same as that of water supply conduits. The calculation of water demand and undelivered water flow for these components in WaterMet^2 follows the same rule as Eq. (3 3) and (3 4). Likewise, the flows of energy, GHG emissions and O&M cost are calculated similarly for these components.

Service Reservoirs

The main function of service reservoirs is to store treated potable water close to the point consumption prior to distributing between subcatchments. Service reservoirs in WaterMet^2 are fed by WTWs through trunk mains and they distribute water demand through distribution mains (see Figure 3 9 and Figure 3 12). Each service reservoir can be connected to any number of subcatchments but the share of each subcatchment needs to be specified by the user. The main characteristics of water flow for each service reservoir in WaterMet^2 are storage capacity, initial volume for the first day and annual water loss. The function of service reservoirs is the same as that described earlier for surface water type in water resource components. Thus, the volume of each service reservoir is calculated at each time step of simulation based on the daily mass water balance between inflows and outflows of the service reservoir similar to Eq. (3 1) and (3 2). Overflow occurs if the volume of a service reservoir exceeds its capacity but this cannot happen because the requested inflow is always less than or equal to the downstream water demand. The main difference is in the size of storage capacity in which it is typically much smaller for this component than that for water resource and thus service reservoirs can only be considered as a short-term storage for fulfilling water demands in the case of water scarcity. Operational costs for each service reservoir in WaterMet^2 comprise fixed annual operational cost and average chemical cost. The flow of chemicals is also tracked down for each service reservoir by specifying chlorine as a water disinfectant. This represents the only agent for flows of GHG emission, acidification and eutrophication in service reservoirs.

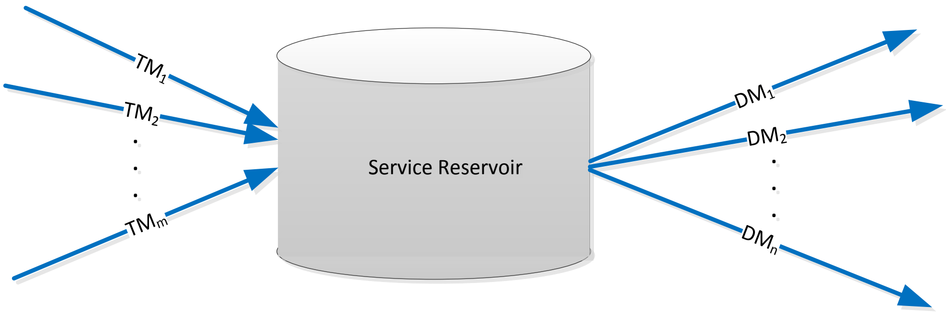


Figure 3 12: Schematic diagram of Service Reservoir and its connected routes modelled in WaterMet²

Distribution mains

Distribution mains are the last component in the water supply subsystem, which conveys potable water to the point of consumption (see Figure 3 9). Distribution mains in WaterMet² are characterised by a number of constant parameters over the planning horizon. These parameters are as follows:

- Daily water transmission capacity,
- Leakage percentage,
- Annual rehabilitation,
- Specific energy required for the distribution of a unit volume of water in the form of both electricity and fossil fuel,
- Fixed annual operational cost.

Calculation of different flows in distribution mains is similar to other types of routes (i.e. conduits and trunk mains). The only difference is in the performance of the leakage in distribution mains. The leakage is defined by the user as a fixed percentage of transferred water in water mains. This percentage is considered to be constant over the planning horizon as long as the annual pipeline rehabilitation is fixed. This is based on assumption that the annual pipeline rehabilitation compensates the rate of pipeline deterioration. However, the leakage percentage in distribution mains is assumed to decrease if the annual pipeline rehabilitation rate is increased within the planning horizon. Note that this rate is defined as a constant value when constructing a WaterMet² model. Therefore, changing this rate in a specific time can be done through defining an individual intervention option in the DSS and out of the WaterMet² model.

As noted above that WaterMet² is a conceptual, mass balance based simulation model, it simply cannot model variations in pressure heads and hence cannot calculate the leakage variations at the daily level. As a compromise, the model assumes the total leakage can be expressed as a percentage of water demand. This can be considered as a reasonable approximation for the long-term, strategic level assessment of the UWS performance. This assumption can be considered as a reasonable approximation for the long-term, strategic level assessment of the UWS performance and was made by other similar models such as UVQ (Mitchell and Diaper 2010), UWOT (Makropoulos *et al.* 2008) and CWB (Mackay and Last 2010).

Furthermore, the flow of materials is also tracked down in distribution mains based on pipeline materials. The pipeline database for each subcatchment is characterised by material type, length, diameter and age. The flow of materials is analysed based on the 'oldest first' approach for pipeline rehabilitation based on a specific amount of annual pipeline rehabilitation rate (Venkatesh 2012). The consequence of material flow (i.e. pipeline rehabilitation) is reflected in flows of *cost*, *energy* (i.e. fossil fuel and embodied energy for pipeline rehabilitation) and *GHG emissions* and general system performance (i.e. *leakage* as outlined above).

3.2.2. Subcatchment

Subcatchment area in WaterMet^2 includes both water demand points in water supply subsystem outlined above plus wastewater collection points in wastewater subsystem outlined in the next section. More specifically, a subcatchment area deals with the water demand, generated sanitary sewage and rainfall-runoff modelling. All these three parts are specified and handled through the local areas defined in each subcatchment. This section only deals with water demands and the other two issues will be discussed in the next section.

Water Demand

Water demand subsystem comprises all water consumption points including both drinking and non-drinking water in the UWS. Drinking water demand can only be supplied through water distribution network outlined above while non-drinking water demand can be supplied by either potable water sources (i.e. water distribution network) or non-potable water sources (e.g. rainwater harvesting scheme). This section describes how different types of water demand are modelled and calculated in different components and how they are supplied by different available sources in WaterMet^2.

Water demand subsystem deals with three lower spatial levels of the UWS (i.e. subcatchment, local area and indoor area). More specifically, WaterMet^2 divides the urban water demand into two main categories of indoor and outdoor water usages which are defined at two levels (i.e. indoor area and local area). Then, these water demands are met at either local area or subcatchment levels. More specifically, local area can only satisfy non-drinking water demand through decentralised water treatment options (i.e. rainwater harvesting and grey water recycling schemes) while subcatchment can cope with both drinking and non-drinking water demands. The following sections describe the configuration of the water demand and supply in these three levels from bottom-up in more detail.

Indoor Area Water Demand

WaterMet^2 supports two levels for defining indoor water demand: (1) the first one is to simply define the indoor water consumption per capita per day; (2) a further detail of indoor water consumption can also be supported in WaterMet^2 by specifying percentage share of a range of water consuming appliances and fittings used in the indoor area. More specifically, the appliances and fittings supported by WaterMet^2 are: (1) hand basin, (2) bath and shower, (3) kitchen sink, (4) dish washer, (5) washing machine and (6) toilet. Note that specifying a percentage share for the appliances and fittings in WaterMet^2 model requires more data but also allows the user to model a range of intervention strategies related to the water demand management and decentralised water treatment options.

When using appliances and fittings for indoor water demand, the principal flows and storages represented in Figure 3 13 will be used for specifying different water streams on indoor area. As shown in the figure, each water outflow at this level is connected with the relevant flows/storages at the next levels. Note that the user is able to define appliances and fittings not only for domestic water demand but also for other types of water consumption. For example, the appliances and fittings for commercial water consumers can only account for toilet and hand basin. Thus, this will enable the user to effectively assess the impact of different appliances and fittings on the sustainability and performance criteria. Alternatively, in the case of limited data available to apply appliances and fittings, the user is still able to continue modelling using only water consumption per capita. Finally, note that the above detailed information can be provided only for the representative, i.e. typical houses/properties (unless a very small spatial area is modelled using WaterMet^2, to e.g. investigate some specific, local issue) - see also next section.

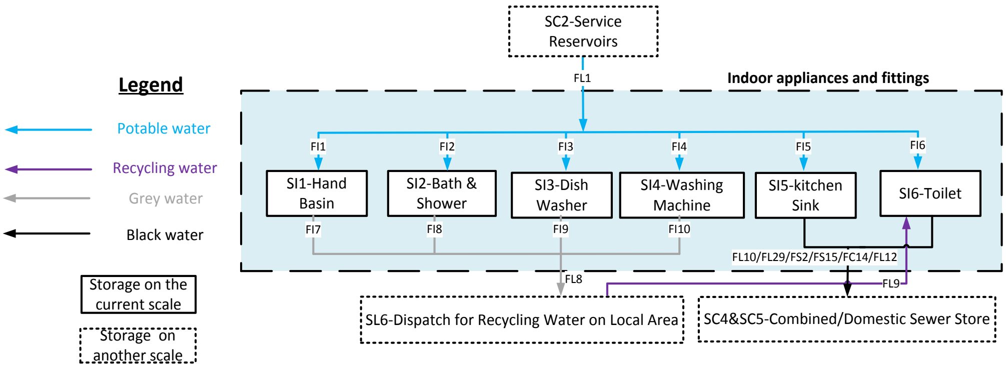


Figure 3 13: Water flows and storages on indoor area

Local Area Water Demand

Specifying water demand and coping with it at consumption points are of the main tasks handled by local area in WaterMet^2. All types of water demand defined in a local area are: (1) indoor water; (2) industrial/commercial; (3) irrigation; (4) frost tapping; (5) unregistered public use. The unit of all water demand types are m^3 per day except indoor water demand which is m^3 per day per capita. For the latter, an average of occupancy for the defined indoor water demand needs to be specified.

WaterMet^2 recognises the variations of water demand in three temporal scales as follows:

1. On the first large scale, annual variations over the planning horizon are defined as the coefficients of annual growth for four types of water demand including (1) indoor as a representative for population; (2) industrial/commercial; (3) irrigation and (4) frost tapping. This typically can be used for defining different scenarios of water demand growth in the UWS.
2. The second temporal scale is monthly variations of water demand in which monthly pattern coefficients are specified for all five types of water demand including the four abovementioned water demands plus unregistered public water demand. This typically can be used for model calibration purposes.
3. The third temporal level deals with daily variations of the five abovementioned water demands. This level provides a more flexibility for daily water demand variations by (1) defining up to two time periods for each of water demand type; (2) correlating each type of daily water demand to the temperature variations.

More specifically, contribution of temperature variations in the third level is added to each type of water demand by the following relation:

$$Cd_{ijk} = \left(1 + \frac{T_k - T_{ave}}{T_{max} - T_{min}} \times F_{ij} \right)$$

3-5

where Cd_{ijk}=coefficient of daily variations for demand category i, local area j and day k; F_{ij}=fluctuation factor accelerating the temperature effect for demand category i and local area j; T_k=Temperature for day k; T_{max} and T_{min}=absolute maximum and minimum temperature of the study area, respectively. It is recommended that coefficient F_{ij} is defined between -1.5 and +1.5 in order to avoid generating minus value for coefficient Cd_{ijk} although any minus coefficient if generated is converted to zero. Finally, the actual water demand for category i, local area j and day k of the year M(Da_{ijkM}) can be calculated as

$$Da_{ijkM} = D_{ij} \times Cd_{ijk} \times Cm_{ij} \times \sum_{m=1}^{M} Ca_{ijm}$$

3-6

where *Dij*=average water demand for category *i*, local area *j*; *Cmij*=coefficient of monthly variations for category *i* and local area *j*; and *Caijm*=coefficient of annual variations for category *i*, local area *j* and year *m*. Water demands in WaterMet^2 can be satisfied by different types of water resources. Potable water from distribution mains is the default water supply but the user can allocate other water sources (i.e. rainwater harvesting and grey water recycling) from decentralised and centralised systems. This allocation is specified for each type of water demands located at different local areas and subcatchments. If there are two or more water source types available, the priorities adopted by WaterMet^2 are: (1) rainwater at local area; (2) grey water at local area; (3) rainwater at subcatchment; (4) grey water at subcatchment; (5) treated grey water from centralised system (i.e. WWTWs); (6) potable mains water. The first five options are available only when the user defines the relevant tanks and activate the allocation of water reuse for water demand profiles. The principal water flows and storages modelled in local area scale are represented in Figure 3 14. As shown in this figure, 'dispatch' with five inflows has the task of allocating water reuse between relevant water demands. The main components and processes modelled by WaterMet^2 only on this level are: (1) local area rainwater harvesting tank; (2) local area grey water recycling tank; (3) rainfall-runoff modelling on pervious and impervious surfaces. More details of the first two components and the last are described in section 3.2.4 and 3.2.3, respectively.

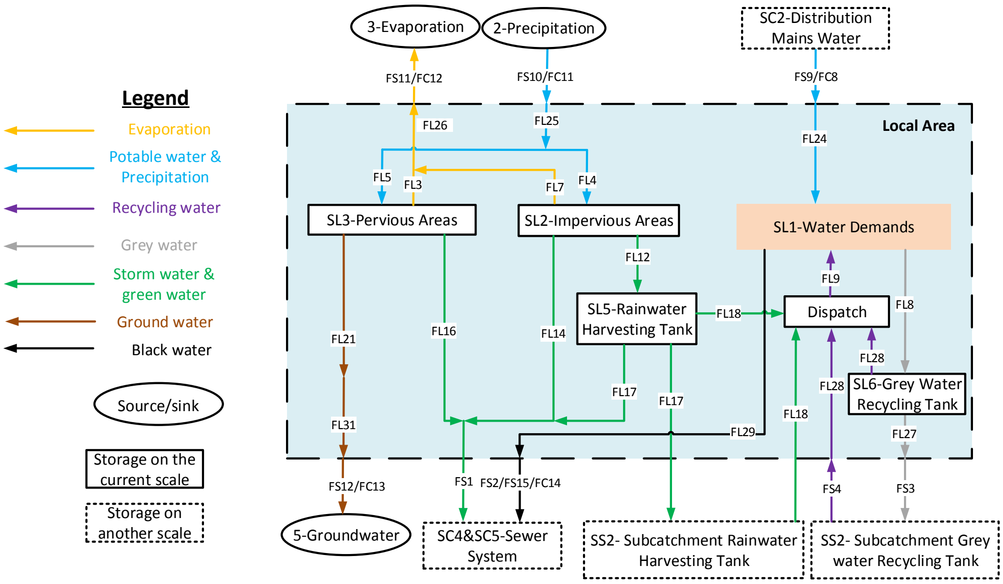


Figure 3 14: Water flows and storages on local area

Subcatchment Water Demand

Figure 3 15 shows all the flows at this level which are associated with the relevant flows/storages at the next levels (i.e. local area as the lower level and city area as the upper level). As shown in this figure, the main external inflows at this level correspond directly with the inside local areas. Of three main external inflows at subcatchment area, mains water and centralised recycling water are related to water demand. They are automatically allocated between potable water demands in local areas. Two components particularly defined on this level are: (1) subcatchment rainwater harvesting tank; (2) subcatchment grey water recycling tank. More details of the functions for these two components will be discussed in section 3.2.3.

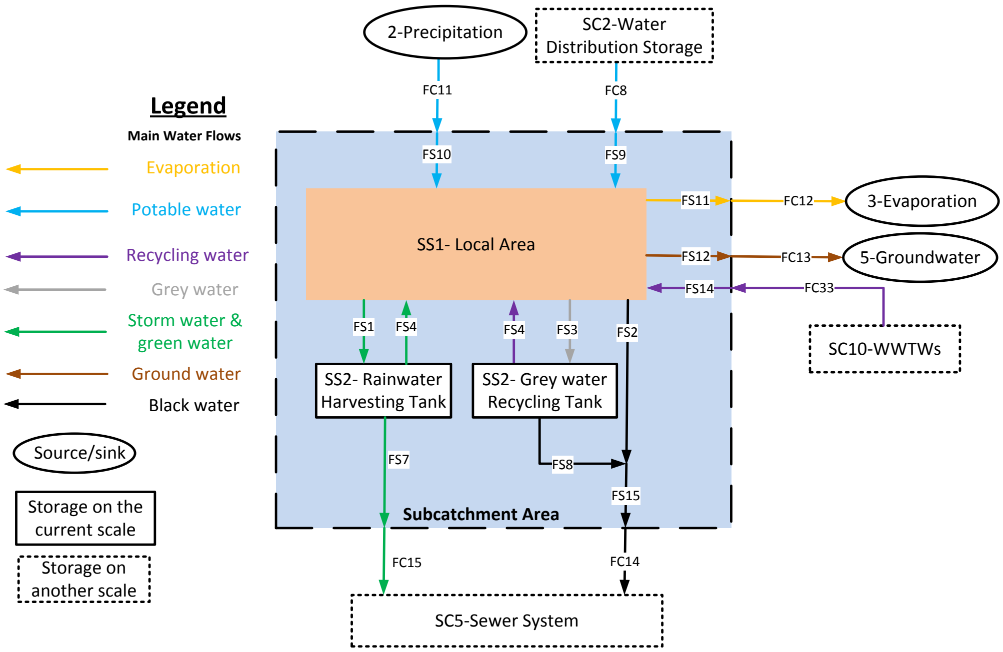


Figure 3 15: Water flows and storages on subcatchment area

3.2.3. Wastewater Subsystem

A simplified approach for wastewater subsystem is also considered by WaterMet^2. The key elements modelled in this subsystem are: 1-principal wastewater/storm water flow 'routes' (denoting mainly combined/separate draining routes between subcatchments modelled); 2-WWTWs and 3- receiving waters (only as a 'sink' point). An example of the main components of a wastewater subsystem collecting wastewater/storm water from different subcatchments of the schematic UWS is presented in Figure 3 16. In this figure, two individual sewer systems are defined independently for two catchments of the UWS based on the topology of the system. The collected storm water/ wastewater of local areas located inside a subcatchment (represented by red solid circles) discharges into the catch basin of the same subcatchment (represented by black solid rectangles). The sewer system is sequentially connected between different catch basins associated with different subcatchments based on the gravity of storm water/wastewater collection systems. Further details of the modelling assumptions adopted in WaterMet^2 for the relevant components and processes are discussed in the following sections.

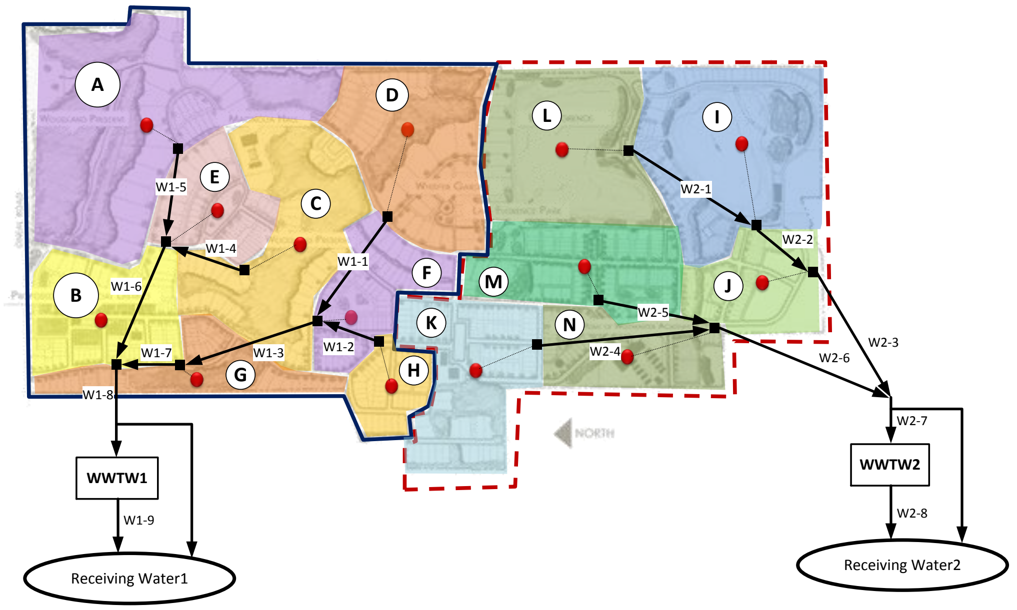


Figure 3 16: An example of wastewater subsystem representation in WaterMet²

Rainfall-Runoff

WaterMet² uses a simple rainfall-runoff algorithm inspired by rational method (Maidment, 1992) and popular SWMM model which assumes 100% runoff from impermeable surfaces (Gironás *et al.*, 2009). The rainfall-runoff simulation is modelled only on local area level as the smallest hydrologic unit of study area. A local area is divided into two surfaces: (1) pervious area; (2) impervious area. The impervious area has no infiltration and only depression storage which transforms the whole rainfall to runoff. The impervious area in WaterMet² is further divided into two parts: (1) roofs and (2) pavements and roads. The benefit of defining two distinct impervious areas is due to possibility of considering any of these two as independent sources for rainwater harvesting scheme in a local area. Thus, the daily volume of runoff *(V)* for each local area is calculated as follows:

$$V = C \times h \times (A_{Roof} + A_{Road} + (1-i) \times A_{Pervious}) \tag{3-7}$$

where C=runoff coefficient between 0 and 1; h= height of daily rainfall and snowmelt; $A_{roof,}$ A_{Road}, $A_{Pervious}$=total area of roof, road & pavement and pervious areas in a local area, respectively; i=infiltration coefficient for pervious areas between 0 and 1 to account for infiltration through garden, park and open spaces in urban areas. For rainfall-runoff modelling, precipitation in both forms of rain and snow plus evaporation is modelled in waterMet^2 by a time series of climate data as input data. The user enters this climate data including precipitation amount, snow depth, precipitation type, mean temperature, average wind speed, hours of sunshine, mean relative humidity, vapour pressure as a daily basis over the planning horizon. The main assumptions associated with rainfall-runoff process in WaterMet^2 are:

- The precipitation as one of variables in the climate time series is accounted for the rainfall height depending on the type of precipitation for a day. There are three types of precipitation (i.e. rain, sleet and snow) which can be considered for precipitation of a day. For the case of 'rain', the full amount of precipitation is considered as the height of rainfall. For 'sleet', half of the precipitation amount is considered as rainfall height. Finally, no rainfall is considered for the case of 'snow'.
- Snowmelt is calculated based on the difference between two consecutive daily snow depths multiplied by snow gravity if a decrease in the daily snow depth is observed.
- The daily evaporation calculated based on the "preferred" method for estimating evaporation rate from open water (Maidment, 1992) is subtracted from the height of rainfall and snowmelt (*h*) before the amount of generated runoff is calculated. The required parameters for calculating evaporation are average wind speed, hours of sunshine, mean relative humidity, vapour pressure.
- The climate parameters are distributed spatially uniform and temporally within the city area during each day.
- The runoff generated in the local areas of a subcatchment is aggregated for each subcatchment and contributes to the basin of the respective subcatchment separate/combined sewer systems. This aggregated runoff for each subcatchment is collected at the subcatchment outlets.

There are two distinct storages defined in the level of local area in Figure 3 14 related to rain-fall runoff modelling including impervious and pervious areas. Imperviousness tends to be the most sensitive parameter in the hydrologic characteristics ranging from 5% for undeveloped areas up to 95% for high-density commercial areas (Gironás *et al.* 2009). The pervious area at which surface runoff can infiltrate include open spaces and irrigation lands such as private/public gardens and parks. As shown in Figure 3 14, both storages have only one inflow (i.e. precipitation). Two out of three outflows in these two storages are identical, i.e.: (1) surface runoff outflow into the sewer system; (2) evaporation which is subtracted before runoff is generated. The third outflow of the impervious storage is the inflow for rainwater harvesting tank in local area if it is activated in WaterMet^2. The third outflow in the pervious storage is related to the portion of water which is infiltrated into groundwater.

Sewer systems

The WaterMet^2 model uses a simplified and conceptual model for both separate and combined sewer systems on city level. In this conceptual model, storm water and wastewater are collected by flow routes from the catch basin (most downstream outlet point) of each subcatchment featured by a black rectangle in Figure 3 16. The inflow of the sewer systems are storm water runoff and sanitary sewage which are collected by wastewater and storm water routes, respectively. The storm water runoff and sanitary sewage for all local areas of each subcatchment are aggregated and entered to the sewer system at the subcatchment outlet point. A user defined percentage of consumed water (typically over 90% for domestic and 85-95% for nondomestic (Metcalf & Eddy 2003)) is converted to sanitary sewage (grey water and black water) and the rest is assumed to be lost. The sewer systems transport sanitary sewage/storm water runoff to WWTWs for treatment. The principal assumptions for the sewer system in the WaterMet^2 model are outlined below:

- Sewer systems are characterised by storm water/wastewater routes specified for each subcatchment. Each subcatchment route connects outlet of the subcatchment to the outlet of the immediate downstream subcatchment (e.g. w1-1, w1-2 in Figure 3 16). These routes are sequentially connected to each other as the tree shape of the gravity of storm water runoff/sanitary sewage collection systems.
- The collected storm water/ wastewater of a subcatchment can be discharged into only one outlet of the downstream subcatchment. However, it can be directly connected and drained to two or more WWTWs. In this case, a percentage coefficient for splitting flow between each WWTW needs to be specified.
- Collecting storm water runoff/sanitary sewage for two or more upstream subcatchments to a downstream subcatchment is allowed (e.g. subcatchments D and H discharging into subcatchment F through W1-1 and W1-2 collection flow routes in Figure 3 16).
- Type of sewer route for each subcatchment needs to be specified as either a combined or separate. For the case of combined, the subcatchment will only have a combined sewer route and for the case of separate, the subcatchment will have both types of sewer routes (i.e. sanitary and storm routes). For either of them, the connected downstream subcatchment needs to be specified for the defined routes.
- Each route in combined sewer has CSO (combined sewer overflow) with a daily capacity but in separate sewer, STO (storm tank overflow) with a daily capacity is also assigned to each storm route. Note that CSO and STO structures divert the excess volume of the sanitary sewage/storm water runoff exceeding their daily capacity, respectively.
- The diverted excess flow in the case of CSO or STO needs to be discharged into receiving waters. Thus, at least one receiving water body needs to be defined for each subcatchment. In the case of defining two or more receiving waters for a subcatchment, a percentage coefficient for splitting overflow between each of the receiving water needs to be specified.
- The capacity of each subcatchment route (either combined/sanitary or storm) can be defined in two ways: (1) without storage in which a daily

transmission capacity is defined; and (2) with storage in which a storage capacity (V) is defined and the outflow (Q) from the storage is determined as follows:

$$Q = a \times V^{b} \quad (3\text{-}8)$$

where *a* and *b* are the parameters which need to be adjusted in the model calibration process. Note that if the volume of sewage/storm water discharging into a sewer system exceeds the daily transmission capacity (in case of sewer "without storage") or the volume of storage (in case of sewer "with storage"), the extra flow (or overflow) is assumed that does not enter the sewer system and thus treated as excess combined/storm water in WaterMet^2.

- For each subcatchment route (either combined/sanitary or storm), an infiltration and exfiltration rate are specified as flow percentage to consider the amount of water inflow and outflow within the flow route, respectively. Note that the exfiltration for combined/sanitary route can cause discharging untreated sanitary sewage to the environment.
- Similar to the flows of pipelines in water distribution network, flows of pipelines in sewer systems will be analysed for each subcatchment based on a user defined annual rehabilitation rate. This annual rehabilitation rate specifies the total length of pipelines which are going to be rehabilitated based on the pre-specified rehabilitation methods. Selection of the pipes for rehabilitation is based on 'old first' approach (Venkatesh 2010). Consequently, material flows are quantified using the pipe lengths. As well as calculating material flow, the relevant cost and GHG emissions are calculated.
- Each sewer route calculates energy, associated GHG emission and relevant costs based on the amount of sewage/storm water transported and the amount of energy and costs required per unit volume of transportation.

Wastewater Treatment Works (WWTW)

The WaterMet^2 allows modelling wastewater treatment at WWTWs on city level as the final destination of combined/sanitary sewer systems. In WWTWs, combined/sanitary wastewater is treated and the productions of WWTWs are treated effluent and resource recovery. Each WWTW can receive wastewater from two or more sewer routes. However, total daily inflow to a WWTW is limited to the daily treatment capacity and storage capacity of the WWTW. Surplus inflow exceeding the sum of the storage and daily treatment capacity will be diverted into receiving water bodies as untreated wastewater.

Chemical flow is calculated for each WWTW similar to the procedure previously outlined for each WTW. Moreover, WWTWs take into account analysing two more flows: (1) contaminant flow; and (2) resource recovery flow. Within the process of the wastewater treatment, the contaminant is removed based on a pre-specified percentage rate removal for each WWTW. Thus, the contaminant load and sludge generated in WWTWs are also calculated based on the complete mixing assumptions (Mitchell and Diaper 2010):

$$L1_{ijt} = L0_{ijt} + V_{ijt} \times C_{ijt}$$

3-9

$$S_{ijt} = L1_{ijt} \times R_{ij} / 100$$

3-10

$$L1_{ijt+1} = L1_{ijt} \times (1 - R_{ij} / 100)$$

3-11

where $L1_{ijt}$, $L0_{ijt}$= load of contaminant j at WWTW i and day t after and prior to mixing with inflow, respectively (kg/day); C_{ijt}= concentration of contaminant j for inflow to WWTW i at day t (mg/l), R_{ij}=removal percentage of contaminant j for wastewater in WWTW i (%/100); S_{ijt}= sludge generated from WWTW i and contaminant j at day t (kg), $L1_{ijt+1}$ = load of contaminant j at WWTW i at day $t+1$ (kg/day).

Flow of resource recovery in WWTWs can be estimated for a number of materials. The amount of generation for each of these materials is calculated by multiplying the volume of treated wastewater by the amount of generated materials per unit volume of treated wastewater in each WWTW. These materials in WaterMet^2 are biogas, ammonium nitrate, single superphosphate and urea.

For each WWTW, the flows of energy (electricity or fossil fuel), chemicals, GHG emission, acidification, eutrophication and O&M cost are calculated as previously outlined in WTWs. Operational costs for each WWTW in WaterMet^2 include electricity, fossil fuel and fixed annual operational costs and average chemical cost. Treated wastewater (outflow of WWTWs) can be used for any of three options (Figure 3 17): (1) discharge into receiving waters; (2) return to subcatchments for water reuse in local areas; and (3) groundwater recharge.

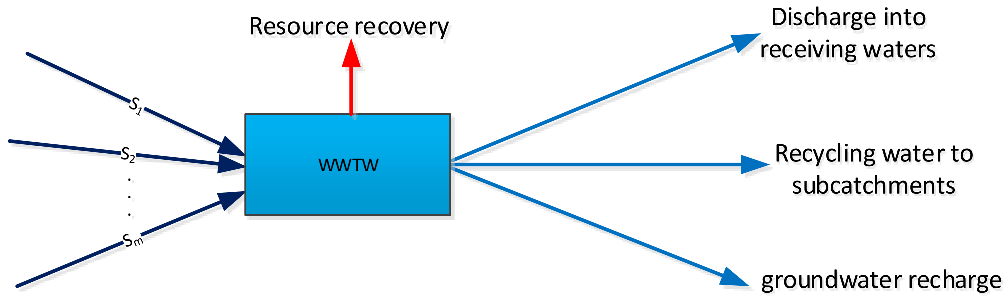


Figure 3 17: inflows and outflows of WWTWs

Receiving water bodies

Receiving waters (e.g. river, lake, wetland, sea, ocean and other watercourses) are modelled as a sink in WaterMet^2 for discharging untreated and treated wastewater. Both flow routes in sewer systems and WWTWs are connected to receiving waters. Untreated wastewater is discharged to receiving waters through CSO structures when the daily flow exceeding the capacity of the relevant sewer route. In WWTWs, both untreated and treated wastewater can be discharged. More specifically, untreated wastewater is discharged when WWTW inflow exceeds the sum of the storage capacity and daily treatment capacity of the WWTW. However, treated wastewater may be discharged if defined by the user. Note that discharge of wastewater from two or more components can be possible in WaterMet^2. Finally, the contaminant flow related to each pre-defined contaminant can be tracked down in each receiving water body over the planning horizon.

3.2.4. Cyclic water recovery subsystem

Cyclic water recovery can be divided into two groups of centralised and decentralised facilities. The centralised water recovery in WaterMet^2 is modelled at city scale. This can be envisaged as recycling treated wastewater of WWTWs between different subcatchments. Decentralised water treatment facilities are modelled in WaterMet^2 in both subcatchment and local area levels as rainwater harvesting (RWH) and grey water recycling (GWR) schemes (see Figure 3 18). Based on IWA classification, the cyclic water recovery options in WaterMet^2 (i.e. RWH and GWR schemes) at the local area and subcatchment scales can be deemed to be a fully decentralised and partially decentralised cyclic water recovery, respectively (IWA 2012).

WaterMet^2 activates recycling water module for satisfying water demands if two requirements are fulfilled: (1) water recycling allocation is activated in water demand profile for at least one water demand type; (2) at least one of the two decentralised recycling water at local area is activated. Once water recycling module is activated, the water demand is satisfied by different water sources based on the priorities described in section 3.2.2. Note that the equations of water mass balance in both water reuse schemes (i.e. RWH and GWR) are defined similarly to the ones in the storage components of water supply system. The contaminant flow is calculated similar to the procedure in WWTWs. Note that both schemes at both levels of local area and subcatchment track down the flows of cost (i.e. capital and O&M), energy (i.e. electricity and fossil fuel) and contaminant.

Both schemes employ a tank in which a storage capacity is specified by the user. WaterMet^2 assumes that the storage volume is first controlled by daily inflow and thus the tank overflow is only affected by inflow and the tank volume left from the previous day. More details of each of these decentralised facilities are described in the following.

Rainwater harvesting (RWH) scheme

Local area RWH scheme can collect runoff from impervious surfaces of a local area and stores in a tank which can be used for non-potable water demands as green water. Figure 3 18 shows inflows, outflows and overflows in a local RHW system modelled in WaterMet^2. Any of these two inflows (i.e. roof runoff and road & Pavement runoff) can be defined by the user as a water source of the local area RWH tank. The outflow can also be defined by the user for any of the eight water demand profiles (i.e. toilet, dish washer, hand basin, kitchen sink, shower, washing machine, industry and irrigation). The water volume exceeding the capacity of the tank overflows directly to only one of the two options (i.e. subcatchment RWH tank and local area GWR tank) specified by the user. If none of them is specified as overflow of the tank, it is discharged into the sewer system.

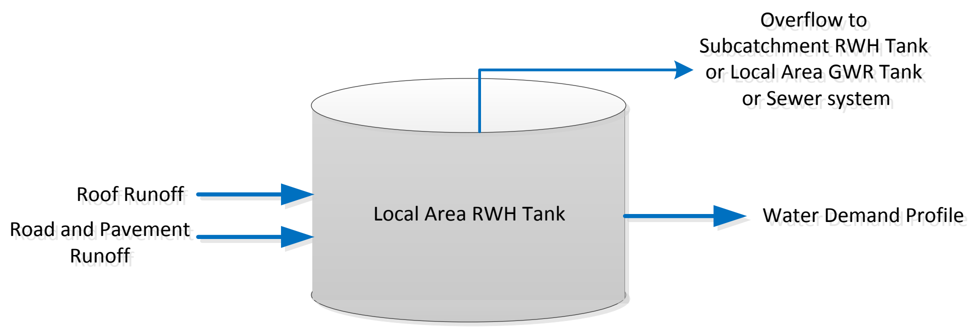


Figure 3 18: inflows, outflows and overflows in local area RWH tank

Figure 3 19 also shows inflows, outflows and overflows in a subcatchment RHW system modelled in WaterMet^2. There are two types of inflow but both are derived from the overflow of local area RWH tank. More specifically, the overflow of the local area RWH tank inside a subcatchment can be directly discharged into the subcatchment RWH tank. If there is any overflow from upstream subcatchment RWH tanks, it can be discharged to the downstream subcatchment RWH tank. There are two options for overflow of this tank that only one of them can be specified by the user. These overflows include: (1) downstream subcatchment RWH tank; and (2) subcatchment GWR tank. Again, if none of them is specified by the user, it is discharged into the sewer system. The outflow of this tank is used for water demand profile similar to local area RWH tank.

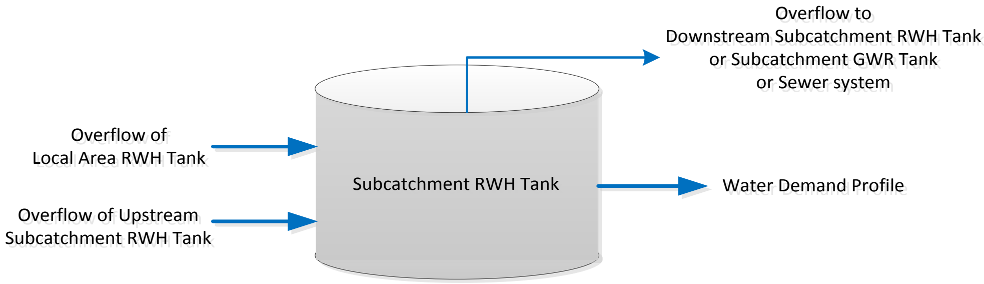


Figure 3 19: inflows, outflows and overflows in subcatchment RWH tank

Grey water recycling (GWR) scheme

GWR scheme can collect grey water and provide recycling water for water demands in a local area. The smallest scale of GWR scheme modelled in WaterMet^2 is at local area and not single household/property (i.e. indoor area) modelled unless that single household/property represents a single local area. Figure 3 20 and Figure 3 21 show the potential inflows, outflows and overflows in local area and subcatchment RWH tanks, respectively. The local area GWR scheme can receive two types of inflow: (1) grey water used in local area including dish washer, hand basin, shower, washing machine, industry and frost tapping; (2) overflow of local area RWH tank. The outflow at both levels is used for water demand profile which is defined by the user. The overflow of local area GWR tank can be discharged into either subcatchment GWR tank (specified by the user) or the sewer system.

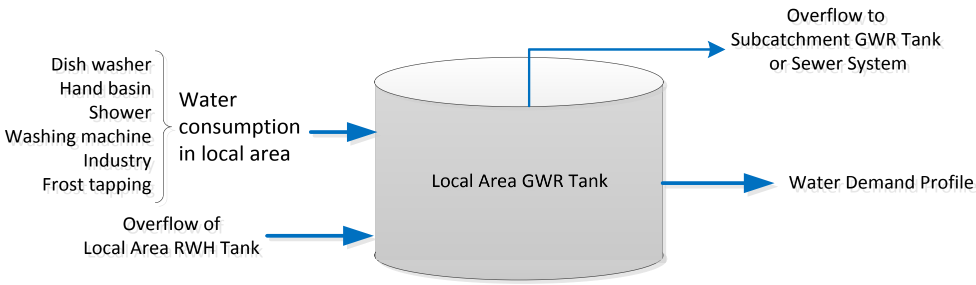


Figure 3 20: inflows, outflows and overflows in local area GWR tank

As shown in Figure 3 21, the inflows to a subcatchment GWR tank can be defined from three tank overflows as: (1) overflows of the local area GWR tank located in the same subcatchment; (2) overflow of a subcatchment RWH tank in the same subcatchment; (3) overflow of a subcatchment GWR tank in the upstream subcatchments. If water volume exceeds the storage capacity of a subcatchment GWR tank, overflow can only be discharged into the sewer system.

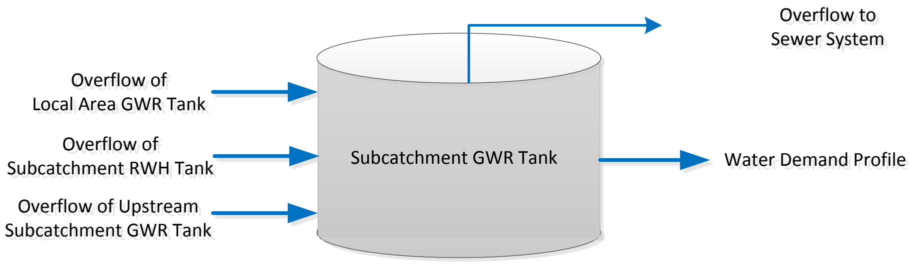


Figure 3 21: inflows, outflows and overflows in subcatchment GWR tank

3.3. Calibration Parameters

The WaterMet^2 model needs to be calibrated before it can be used for any specific application. The calibration process can be performed with data from either historic measurements or the result of physically based models. In the calibration process, the calibration parameters of the WaterMet^2 model are adjusted such that the calculated (prediction) variables closely match the observed data. The calculated variables in WaterMet^2 include the KPIs available in the 'Report' module which will be described in section 4.4. The calibration should apply to the most uncertain parameters in the WaterMet^2 model but any other WaterMet^2 model input data can be calibrated if necessary. Therefore, the most typical calibration parameters in WaterMet^2 include, but are not limited, to the following:

- Storage capacity and water loss in water resources and service reservoirs;
- Treatment capacity in WTWs;
- Transmission capacity and leakage rate in conduits, trunk mains and distribution mains;
- Initial volume in water resources and service reservoirs especially for short-term periods;
- Monthly coefficients of water demand profiles;
- Percentage contribution of daily temperature in daily variation of water demand profiles;
- Water demand profiles in local areas;
- Average occupancy of each property in local areas;
- Rainfall-runoff and infiltration coefficients in local areas;
- Percentage share of pervious and impervious surfaces in local areas;
- Coefficients of storage capacity in sewerage and CSO/STO capacity;
- Infiltration and exfiltration rate in sewerage;
- Treatment and storage capacities in WWTWs.

More details of these parameters and how a WaterMet^2 model is calibrated will be exemplified in the next chapter in section 5.3. In that example, water supply and wastewater subsystems are calibrated separately but sequentially. Note that for calibration of each subsystem, only the relevant parameters of that subsystem outlined above are used in the model calibration process.

4. WaterMet^2 Software Tool

This chapter provides a description of installation and user interface (UI) in the stand-alone software tool of WaterMet^2. When describing various parts of the tool in this chapter, the model is referred to the previous chapters for illustrating the modelling concepts if appropriate. This stand-alone tool can be useful for both types of the users (i.e. normal and advanced). More specifically, they users especially normal (e.g. water utilities/company/consultancy experts) can benefit from the capabilities of the tool to construct a WaterMet^2 model, retrieve and analyse the defined KPIs. Advanced users (e.g. other programming language developers) who aim to do further analyses (e.g. risk analysis and optimisation applications) need to prepare a WaterMet^2 model by the stand-alone tool. These users need to use toolkit functions (described in section 4.5) to customise the model according to their specific needs. In the rest, how to get started with the software is first described. Then, input and output forms will be explained in the next sections.

4.1. Getting started

This section deals with software installation in order to use it for the first time. Before installing the software, the user needs to check the system requirement if they are compatible with the software requirements. After a successful installation, the user can start working on either a new model or existing model. The software tool is freely available for the users and can be accessible through either upon request from the developers or the TRUST website. The users also need to comply with the terms and conditions of the software licence.

4.1.1. System requirements

The system requirements for installing the software are as follows:

- Operating System: Windows 8, Windows Server 2012, Windows 7, Windows Vista SP1 or later, Windows XP SP3, Windows XP SP2 x64 Edition, Windows Server 2008 (Server Core not supported), Windows Server 2008 R2 (Server Core supported with SP1 or later), Windows Server 2003 SP2
- WaterMet^2 uses Windows™ based screens, and navigational devices such as buttons, drop-down menus and toolbars. The Minimum Screen Resolution is 1152x864 but a resolution of 1680x1050 or higher is highly recommended.
- Windows Regional Settings: any language is allowed when installing the software. However, for using the examples in the case study section, it is recommended to set for those languages (e.g. English) which recognises "." as decimal sign in Windows and Microsoft Office.
- Microsoft Excel 2000 or later - English Edition for viewing output files

4.1.2. Installation

The WaterMet^2 model is designed to run under a Windows™ operating system. It is distributed in a folder including a setup.exe file which automatically installs the program on Windows. The following steps are required for installing WaterMet^2:

1. Double click on the setup.exe file in the installation folder.
2. Once the installation wizard window is appeared (Figure 4 1), click Next button to adjust other settings of the programs (i.e. License agreement, Customer information and Destination folder).
3. If the program has been previously installed, a message window will appear and ask the user to select any of three options: Modify, Repair or Remove the program (Figure 4-2). If the user wants to install a new version, Modify option must be clicked.
4. Finally click Install button to begin the setup process.

Figure 4 1: Installation wizard Window for WaterMet^2

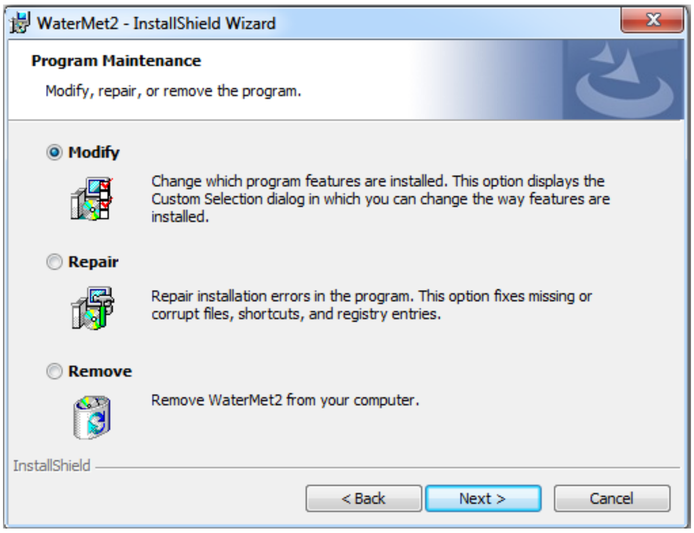


Figure 4 2: Options to reinstall or remove for WaterMet^2.

In the window of "Destination folder", the default folder is c:\Program Files (x86)\WaterMet2\ but the user can choose it to a new folder (directory) where the WaterMet^2 program files will be placed. After installation, a new program named WaterMet^2 is added to the list of programs in the Start Menu. To launch WaterMet^2, the user can either click the executable (WaterMet2.exe) file of the program in the Start Menu or double click on its exe icon (trust) in the Desktop. Note that to remove WaterMet^2 from the computer, the user can remove it from either Start Menu in the folder of 'WaterMet2' under 'Uninstall WaterMet^2' or the conventional procedure for removing a program (i.e. through the Control Panel and Add/Remove Programs).

4.1.3. Overview of WaterMet^2 forms

Figure 4-3 shows the WaterMet^2 main window along with the main forms. The main window contains three main user interface elements: Main Menu, Toolbar, Left Hand Pane. A brief description of each of these elements is provided in the sections that follow. In addition, there are some input and output forms for the WaterMet^2 program. A series of Input Data forms can be used for defining a WaterMet^2 model. The output in WaterMet^2 can be presented as a series of either graphical or tabular format.

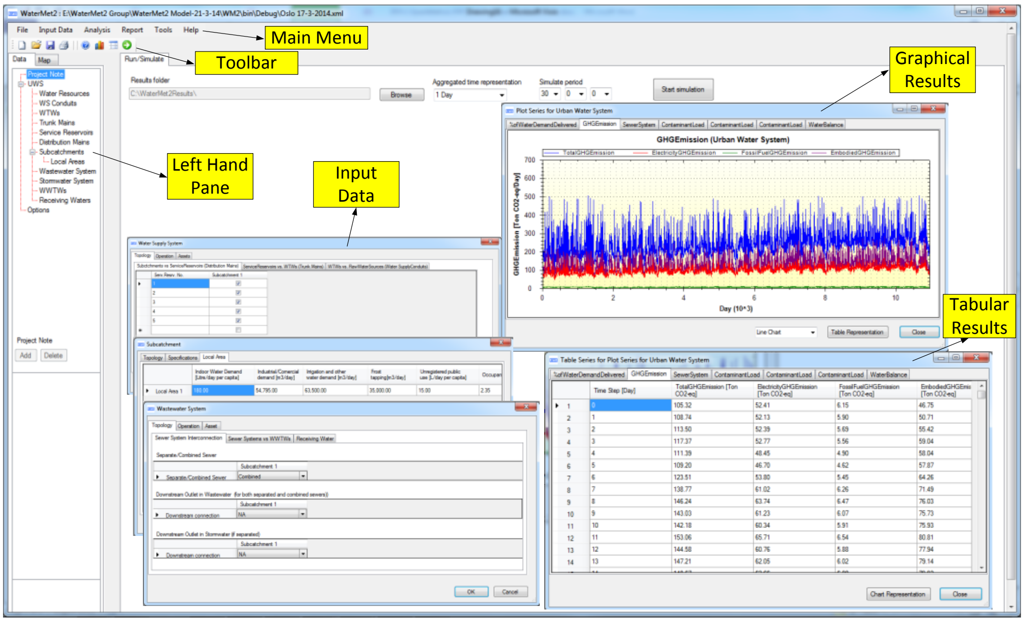


Figure 4 3: Overview of the WaterMet^2 Program

Main Menu

The Main Menu located across the top of the WaterMet^2 main window contains a collection of menus used to control the program. The menus and a brief description of the items in each are as follows:

- File Menu: it contains some basic commands for opening a new, existing file of the WaterMet^2 model, and saving them and so on.
- Input Data Menu: it contains the required forms for defining or editing components in a WaterMet^2 model.
- Analysis Menu: it contains the forms for running a simulation and the relevant settings such as calibration and so on.
- Report Menu: it contains commands used to report analysis results such as tabular or graphical formats.
- Tool Menu: it contains commands used to configure program preferences and options.
- Help Menu: it contains commands for getting help in WaterMet^2.

Toolbar

The Toolbar located underneath the Main Menu bar provides some shortcuts to commonly used operations in WaterMet^2. These shortcuts include:

- New file
- Open file
- Save file
- Print file
- Get help
- Graphical results
- Tabular results
- Run a simulation

Left Hand Pane

This pane located on the left hand side of the main window provides a quick access to the main components in a tree format. Hence, this is an alternative to access the relevant forms of the components of the input data in WaterMet^2. Generally, these forms can be accessible through the Input Data menu. The components represented in this pane are:

- Water resources,
- Water supply conduits,
- WTWs,
- Trunk mains,
- Service reservoirs,
- Distribution mains,
- Subcatchments,
- Local areas,
- Wastewater system,
- Storm water system,
- WWTWs,
- Receiving waters and Options.

4.1.4. Steps in WaterMet^2

When working with WaterMet^2 to model an UWS, the user needs to follow the steps outlined below sequentially:

- Add/define new components in the UWS and specify the relevant topology
- Specify the components' characteristics in the relevant forms
- Specify the constant values in the option form
- Run a simulation
- View/extract simulation results

These steps will be described in the next sections sequentially. More specifically, a review of all input data forms are first explained which will be followed by a description of running a simulation. Different aspects of viewing the simulation results are finally presented.

4.2. Input data forms

The main functionality of the UWS components in WaterMet^2 is defined through the following three forms:

- Water Supply
- Subcatchment
- Wastewater

If the user wants to model only water supply subsystem, the first two forms (i.e. 'Water Supply' and 'Subcatchment') need to be filled out. For modelling an integrated UWS including both water supply and storm water/wastewater subsystems, all three forms must be populated. In addition to these forms, the input data for two additional sections need to be prepared in order to reach a point in which the WaterMet^2 model can be simulated. These forms are:

- Option
- Time Series

All these forms are basic input data forms which are described in the following sections. Additionally, 'Water Resource Recovery' forms can be considered if the user wants to model recycling water in the UWS. These forms are also explained subsequently.

4.2.1. Water Supply

'Water Supply' form consists of three main tabs: Topology, Operation, and Assets. Each of these tabs is separately discussed in the following sections.

Topology

All components in water supply subsystem are defined in 'Topology' tab which is shown in Figure 4-4. This tab consists of three tables:

- **Distribution Mains table** in which new service reservoirs are added and connected to the subcatchments of interest.
- **Trunk mains table** in which new WTWs are added and connected to the service reservoirs of interest.
- **Water Supply Conduits table** in which new raw water resources are added and connected to the WTWs of interest.

Therefore, the steps for adding new components between these tables must follow the order below:

(1) Distribution Mains table,
(2) Trunk Mains table,
(3) Water Supply Conduits table,

Defining new components is only possible through the above order. For instance, if no service reservoir is defined in the 'Distribution Mains' table, defining WTWs and subsequently water resource are not possible in the next two tables.

However, subcatchment in first tab (Distribution Mains) must be defined before the first step. There are two ways to define subcatchments: (1) select **File>>New** button; and (2) select **Input Data>>Subcatchment>>Topology** tab, then click **Add/Remove Subcatchment** button. Note that if the user is in middle of the modelling (i.e. already defined/specified other elements), the second method is appropriate as the first method creates a new model and thus deletes the input data of all the current modelling.

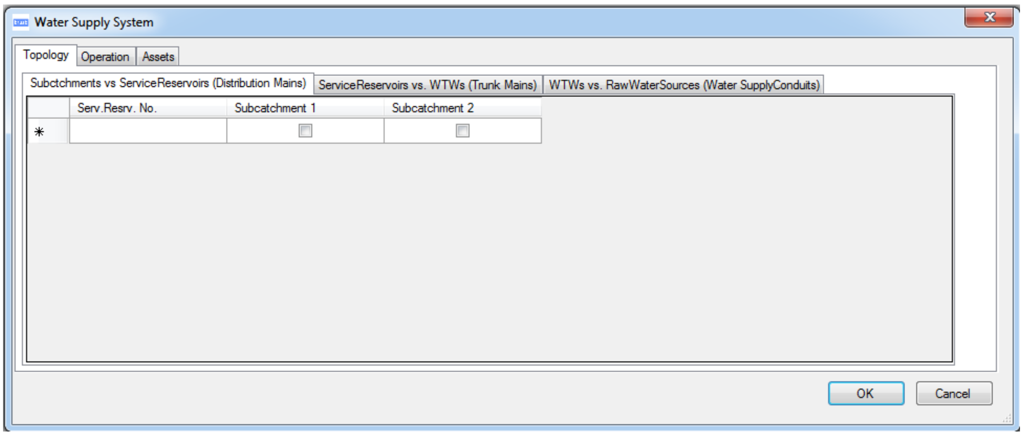


Figure 4 4: 'Topology' tab in 'Water Supply' form

Operation

Having defined the components of water supply subsystem, the allocation coefficients of water demands for each flow route can be filled out in the 'Operation' tab. This tab consists of three tables each of which contains the flow routes associated with those defined in the 'Topology' tab (Figure4-5). For each table, the sum of the allocation coefficients for each component, connecting to one or more upstream components, must be equal to 1. More details of this concept were described in section 3.2.1 of this report. Needless to say, the allocation coefficient for a component which is only connected to one upstream component is equal to 1.

Assets

The final step of defining components in water supply subsystem is to determine the specifications of the components (Figure 4 6). These assets are:

- Water resources,
- Water supply conduits

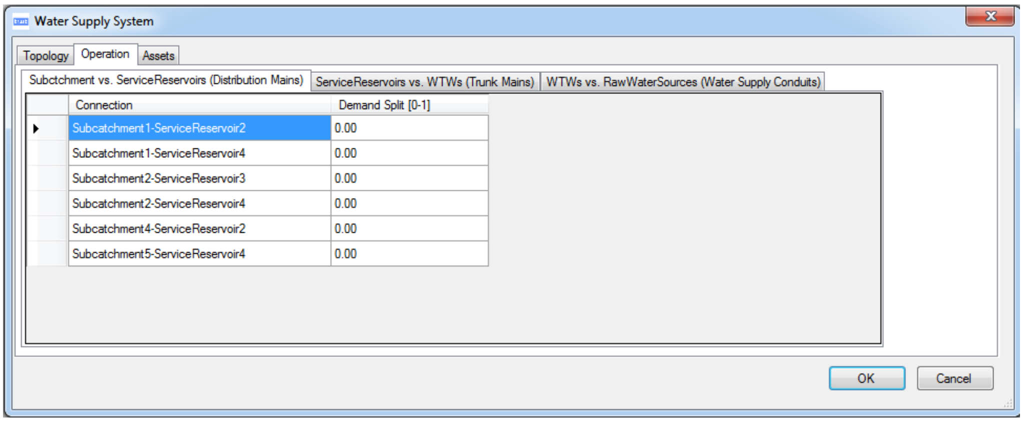


Figure 4 5: 'Operation' tab in 'Water Supply' form

- WTWs
- Trunk mains
- Service reservoirs
- Distribution mains

Each of these assets requires some specific characteristics associated with the conceptual system which is modelled. WaterMet^2 allows the user to specify the type of a water resource from dropdown list of three types: surface water, ground water and desalination. Surface water applies to any water resources such as river, reservoir dam or lake. If surface water is selected, storage capacity and initial volume need to be specified by the user. In addition, for surface water, WaterMet^2 needs the time series of inflows into the storage for applying water mass balance equations. However, in case of ground water or desalination, none of these is required and thus storage capacity and initial volume will be disabled.

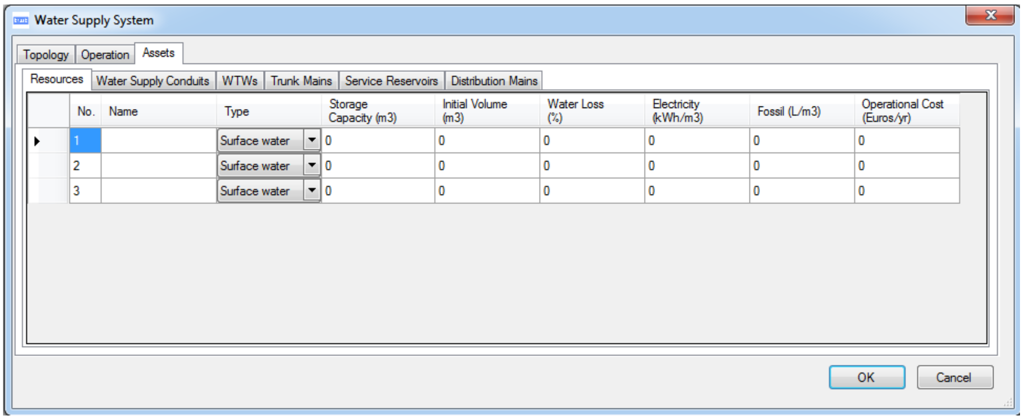


Figure 4 6: 'Assets' tab (Resources table) in 'Water Supply' form

For each WTW or service reservoir, the user can define a variety of chemicals used from a list of available chemicals in WaterMet^2 (Figure4 7). The available chemicals for WTWs in WaterMet^2 are: Alum, Calcium hydroxide, Carbon dioxide, Microsand, PAX and NaoCl. The only chemical which is available for service reservoir is chlorine which is consumed for disinfection in the water distribution network. Note that in the case of defining the same chemicals for a number of WTWs in terms of type and amount, the user can benefit from a dropdown box in the form in which the previously defined chemicals for other WTWs can be simply retrieved for new WTWs and thus there is no need to start specifying all the chemicals again from scratch (Figure4 7).

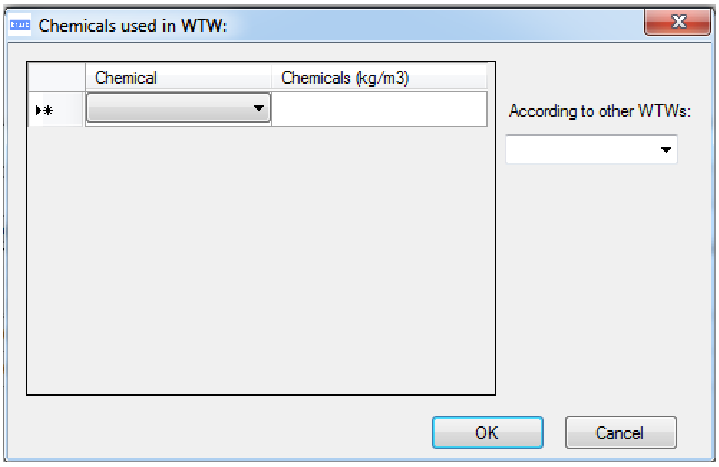


Figure 4 7: 'Chemicals' form in 'Water Supply' form

4.2.2. Subcatchment

The 'Subcatchment' form as shown in Figure 4 8 comprises three tabs: 'Topology', 'Specifications' and 'Local Area'. This form specifically defines the characteristics of subcatchments and local areas. In the 'Topology' tab, the user defines new subcatchments and typical local areas. The number of subcatchments can be changed by clicking the **Add/Remove Subcatchment** button at the bottom of the form. This bottom is only available when the 'Topology' tab is selected. The number of local areas can also be added by ticking any checkbox in the lowest row of the table.

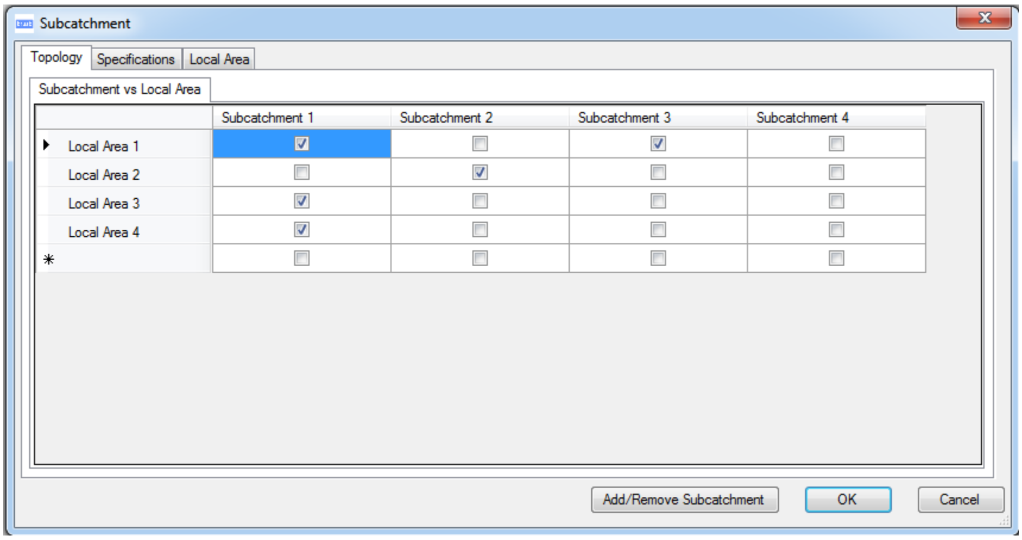


Figure 4 8: 'Subcatchment' form

In WaterMet^2, typical local areas with the relevant basic features are first defined. These basic features are specified in the 'Local Area' tab. Then, each subcatchment picks up a number of typical local areas of interest by ticking the checkbox in the row of the relevant local areas. Then the specific features of those local areas are defined in the 'Specifications' tab (Figure 4 9).

'Local Area' tab shown in Figure 4 10 specifically deals with two sets of basic features: water demand profile and rainfall runoff modelling. More details of the modelling concepts for water demand and rainfall-runoff modelling can be found in sections 3.2.2 and 3.2.3, respectively. The following water demand profile is defined for each local area:

- Indoor water demand with the unit of Litre per day per capita
- Industrial/commercial water demand with the unit of m^3/day
- Irrigation and other water demand with the unit of m^3/day
- Frost tapping water demand with the unit of m^3/day
- Unregistered public use with the unit of m^3/day

Indoor water demand can be defined with further details for appliances and fittings as water consumers. In this case, percentage split coefficients of indoor water demand is specified for typical appliances and fittings including dish washer, hand basin, kitchen sink, washing machine, shower and toilet. All this is specified in the 'Option' form under 'Constant2' tab (Figure 4 26).

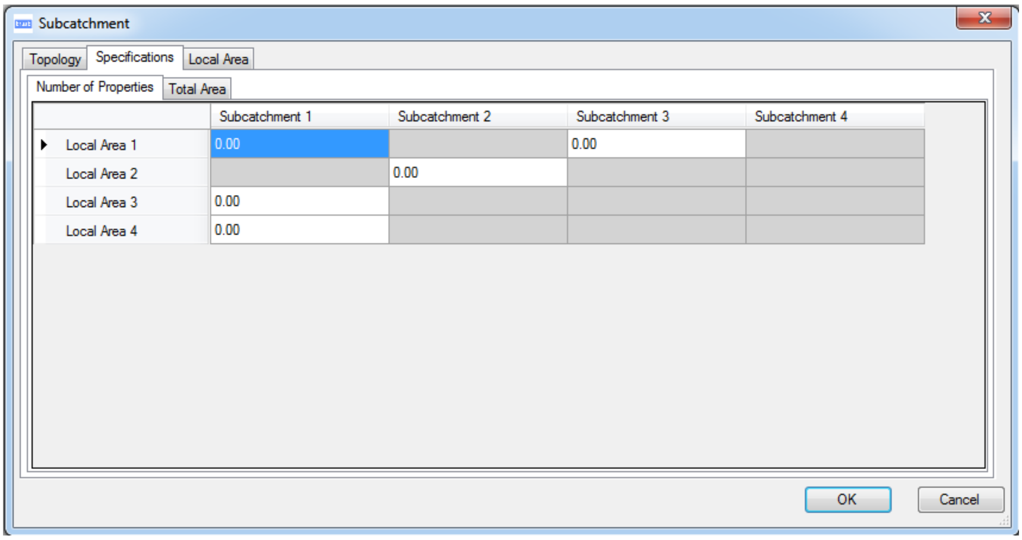


Figure 4 9: 'Specifications' tab (Total Area table) in 'Subcatchment' form

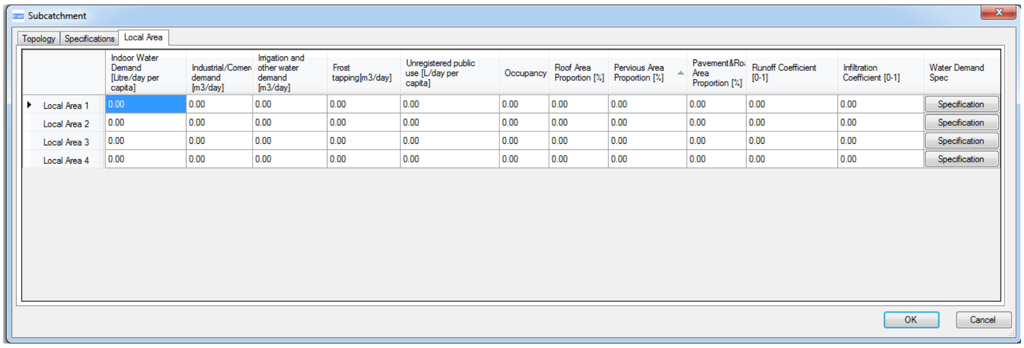
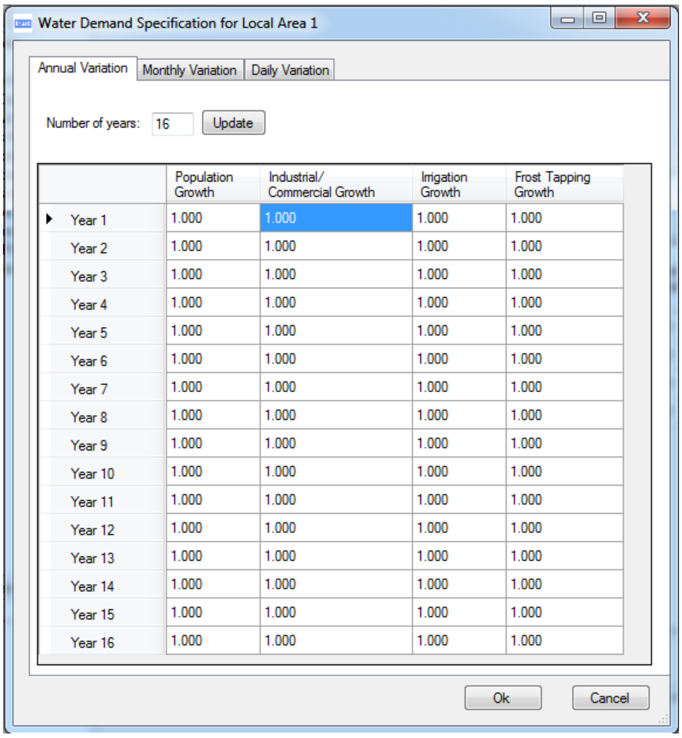


Figure 4 10: 'Specifications' tab (Total Area table) in 'Subcatchment' form

The water demand variations for each local area can be adjusted in three levels: annual, monthly and daily. The annual variations of water demand as shown in Figure 4 11 represents the annual projection for growth/decrease in population, industry, irrigation and frost tapping over the planning horizon. The default value for all variables in this table is set to 1 indicating no annual variations. Note that the number of years should be defined in accordance with the duration of the planning horizon. The monthly variations of water demand shown in Figure 4 12 allow the user to better adjust the calibration parameters such as water productions. The default values for monthly variations are assumed to be 1.



Water Demand Specification for Local Area 1

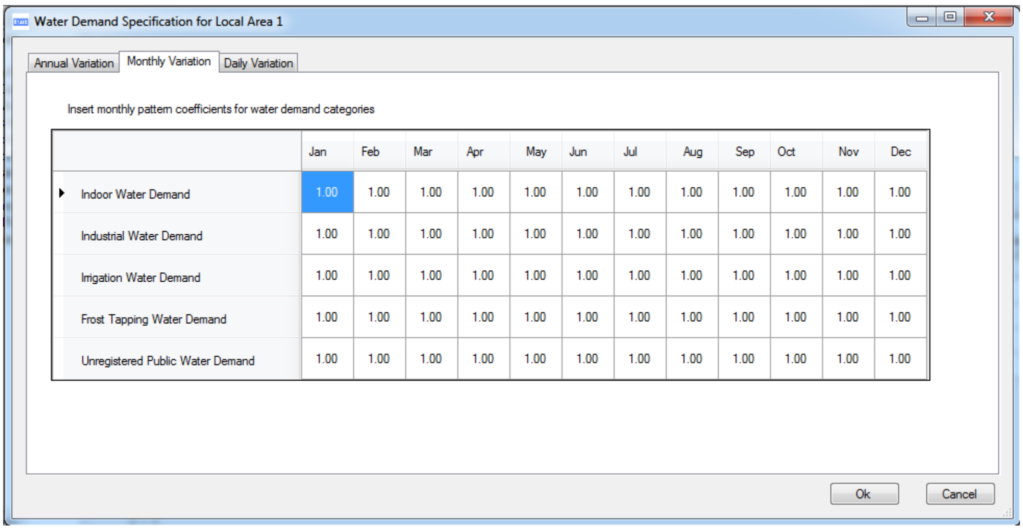
Annual Variation | Monthly Variation | Daily Variation

Number of years: 16 Update

	Population Growth	Industrial/ Commercial Growth	Irrigation Growth	Frost Tapping Growth
Year 1	1.000	1.000	1.000	1.000
Year 2	1.000	1.000	1.000	1.000
Year 3	1.000	1.000	1.000	1.000
Year 4	1.000	1.000	1.000	1.000
Year 5	1.000	1.000	1.000	1.000
Year 6	1.000	1.000	1.000	1.000
Year 7	1.000	1.000	1.000	1.000
Year 8	1.000	1.000	1.000	1.000
Year 9	1.000	1.000	1.000	1.000
Year 10	1.000	1.000	1.000	1.000
Year 11	1.000	1.000	1.000	1.000
Year 12	1.000	1.000	1.000	1.000
Year 13	1.000	1.000	1.000	1.000
Year 14	1.000	1.000	1.000	1.000
Year 15	1.000	1.000	1.000	1.000
Year 16	1.000	1.000	1.000	1.000

Ok Cancel

Figure 4 11: Annual variations of water demand in 'Water Demand Specification' form



Water Demand Specification for Local Area 1

Annual Variation | Monthly Variation | Daily Variation

Insert monthly pattern coefficients for water demand categories

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Indoor Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Industrial Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Irrigation Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Frost Tapping Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Unregistered Public Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Ok Cancel

Figure 4 12: Monthly variations of water demand in 'Water Demand Specification' form

The daily variations of water demand shown in Figure 4 13 takes into account two issues: (1) daily variations of water demand in proportion to temperature. More details of the modelling concepts can be found in section 3.2.2; (2) two sets of on-off water demands for each water demand category over a year. The default values for latter case are one interval with 365 days.

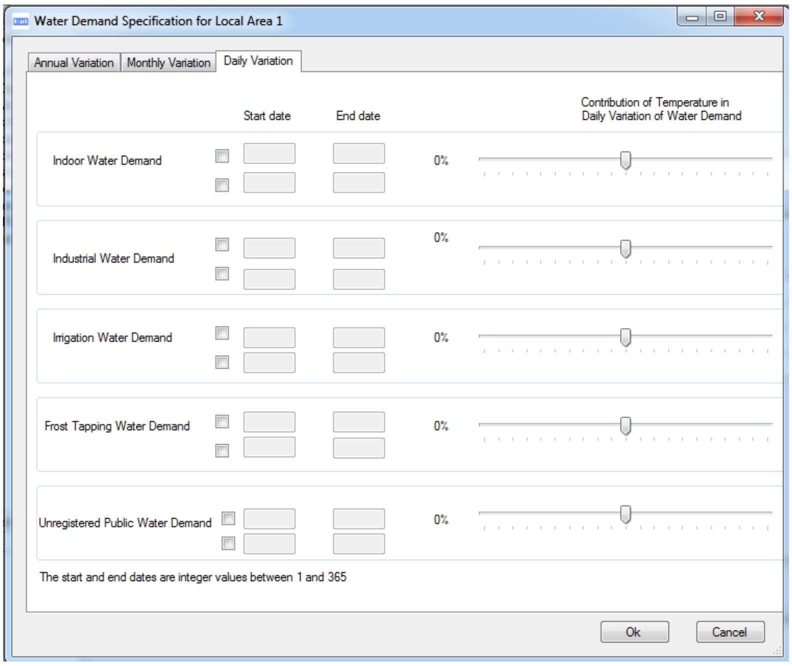


Figure 4 13: Daily variations of water demand in 'Water Demand Specification' form

4.2.3. Wastewater

The wastewater form as shown in Figure 4 14 consists of three tabs: 'Topology', 'Operation' and 'Asset'. In the 'Topology' tab, the user defines how different components (i.e. sewer systems, WWTWs and receiving waters) are connected to each other. These connections in the 'Topology' tab are specified through three tabs: 'Sewer Systems Interconnections', 'Sewer System vs WWTWs', and 'Receiving Water'.

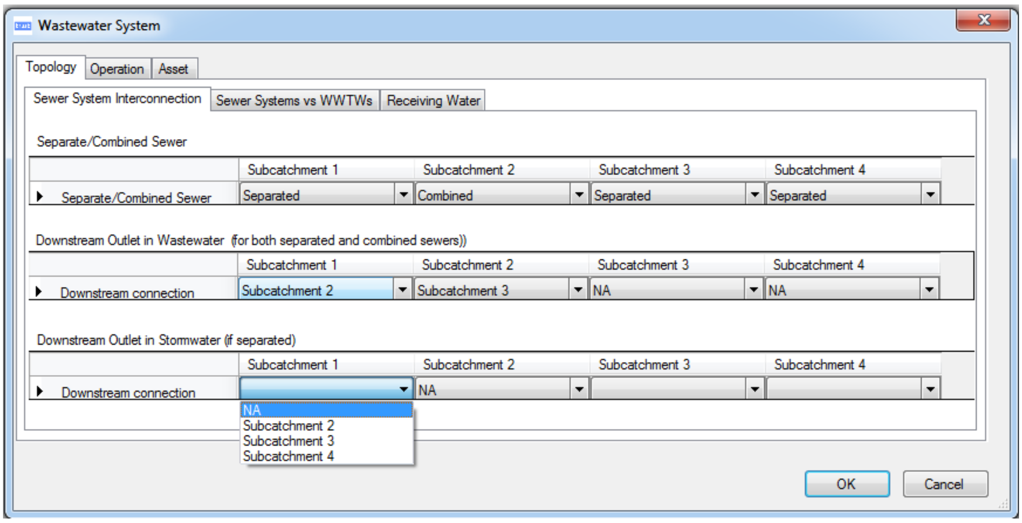


Figure 4 14: Definition of downstream sewer system for a sewer system in the 'Topology' tab

In the first tab shown in Figure 4 14, the user first specifies the type of each sewer system (i.e. combined or separate) in the top part of the tab. Each sewer system is associated with a subcatchment and hence subcatchment name and number used in this tab referred to the respective sewer system. Also, wastewater in each sewer system can only be discharged to either a downstream sewer system or directly a WWTW. In the former case, the user needs to specify the number of downstream sewer system to which wastewater is discharged. In WaterMet^2, number of downstream sewer system (or subcatchment) is greater than the number of upstream sewer system. For instance, the potential downstream sewer systems for sewer system 2 out of 4 sewer systems are sewer systems 3 and 4. In the case of discharging directly to a WWTW, the user needs to specify NA option in the dropdown box for the downstream outlet.

In the second tab of 'Topology' tab shown in Figure 4 15, the user first specifies whether a sewer system (associated with a subcatchment) is connected to a WWTW or not. The user is allowed to specify two or more WWTWs for each sewer system as the discharge points but the percentage coefficients for splitting flow between them needs to be specified in the 'Operation' tab. Selection of a downstream WWTW is allowed only if the user specified that there is no downstream sewer system relative a sewer system. Otherwise, the program will show a warning message. If two or more WWTWs are connected to a sewer system, an information message will notify the user to specify the percentage split coefficient of flow to each of them. Furthermore, the user can define new WWTWs in this tab by ticking any checkbox in the lowest row of the table.

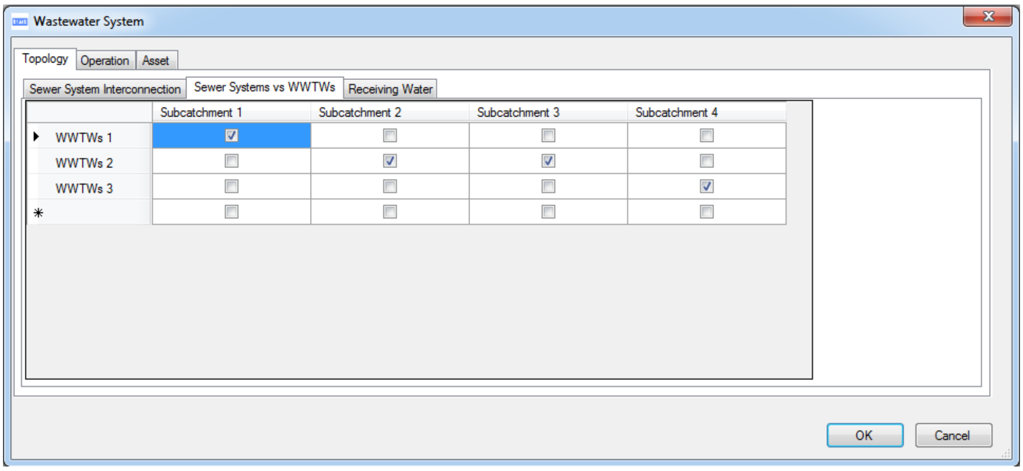


Figure 4 15: Definition of downstream WWTWs for sewer system in the 'Topology' tab

In the third tab of the 'Topology' tab shown in Figure 4 16, the user specifies a receiving water for each of the sewer systems and WWTWs. The user is allowed to specify more than one receiving water body for each component as the discharge point but the percentage split coefficients between them needs to be specified in the 'Operation' tab. Similarly, if two or more receiving waters are connected to a component, an information message will notify the user to specify the percentage split coefficients of flow. In addition, the user can define new receiving waters in this tab by ticking any checkbox in the lowest row of the table.

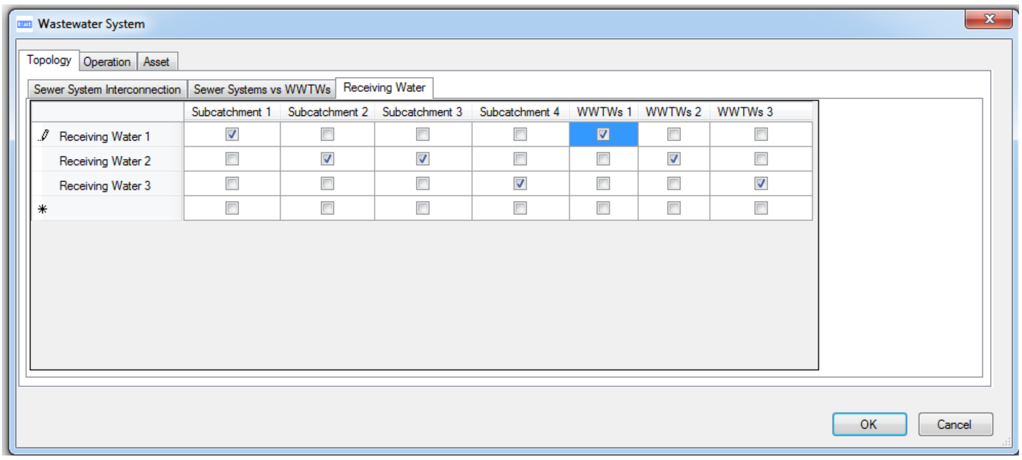


Figure 4 16: Definition of downstream receiving waters for wastewater subsystem components in the 'Topology' tab

In the 'Operation' tab shown in Figure 4 17 and Figure 4 18, the user specifies percentage split coefficients of discharge into the specified downstream components. Obviously, if wastewater is discharged into only one downstream component, the split coefficient is equal to 100. In addition, specifying these split coefficients is allowed only for the specified downstream components and thus the relevant cells for unspecified downstream components are disabled.

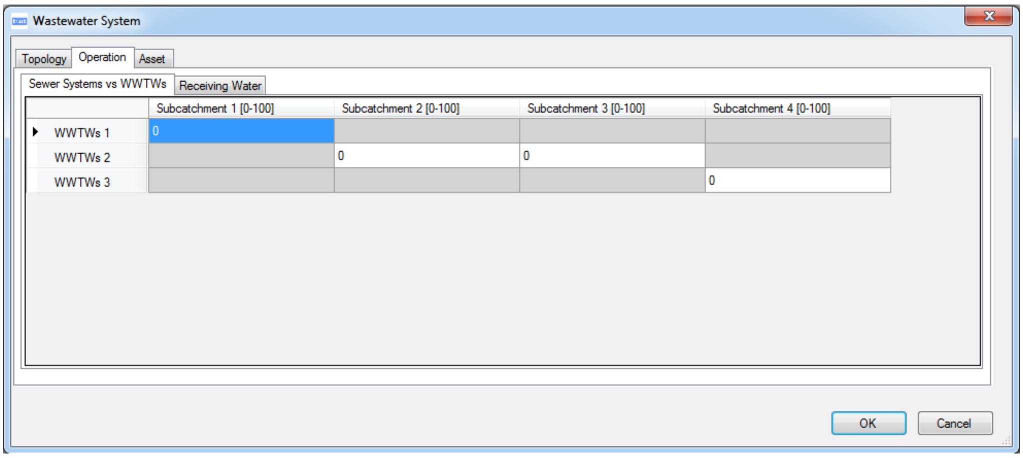


Figure 4 17: Split coefficients between sewer systems and WWTWs in the 'Operation' tab of the 'Wastewater' form

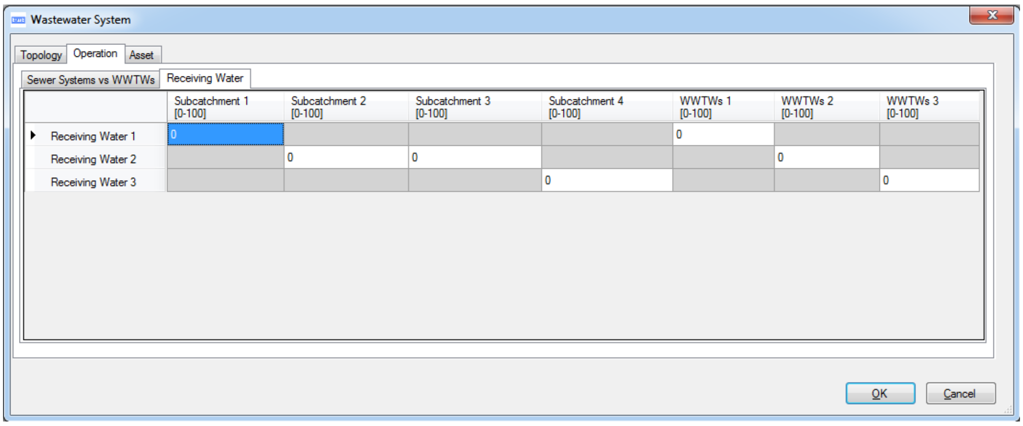


Figure 4 18: Split coefficients between components in wastewater subsystems and receiving waters in the 'Topology' tab of the 'Wastewater' form

The 'Asset' tab of 'Wastewater' form shown in Figure 4 19 consists of four sections: 'Combined/Sanitary Sewer', 'Storm Sewer', 'WWTWs' and 'Receiving Water'. The first two sections of this tab, the user defines the specifications of sewer systems. If the user specified a sewer system as combined, the relevant input data of the sewer system need to be specified for only ‘Wastewater’ tab. However, in case of defining separate sewer system for a subcatchment, the specifications in both tabs (i.e. ‘Combined/Sanitary Sewer’ and ‘Storm Sewer’) need to be filled out.

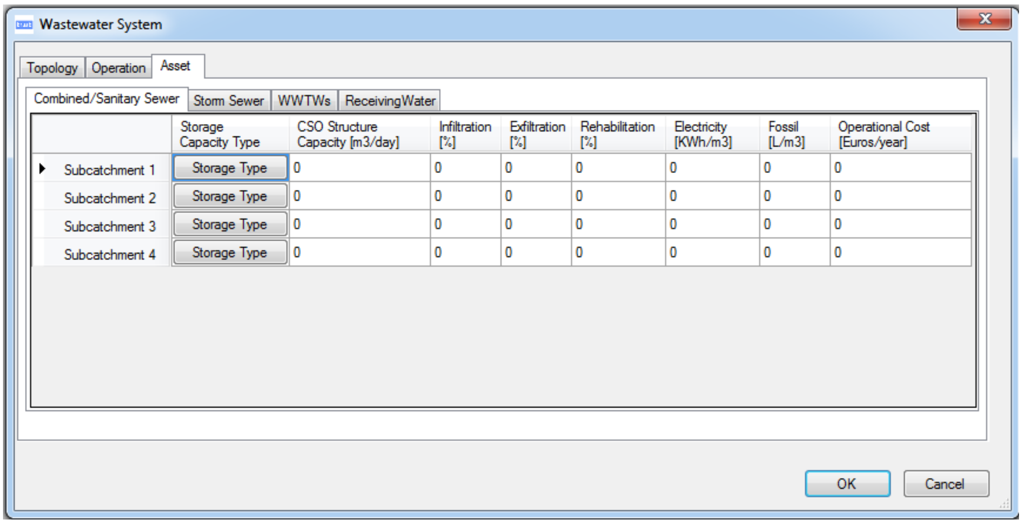


Figure 4 19: Specifications of sewer systems in the ‘Asset’ tab of the ‘Wastewater’ form

WaterMet^2 assumes two types for storage capacity of a sewer system (Figure 4 20): daily transmission capacity without storage and specific storage capacity with a relevant discharge function. The user is only allowed to select either of two for each sewer system. More details of the modelling concepts related to the functionality of different types of sewer system storage can be found in section 3.2.3.

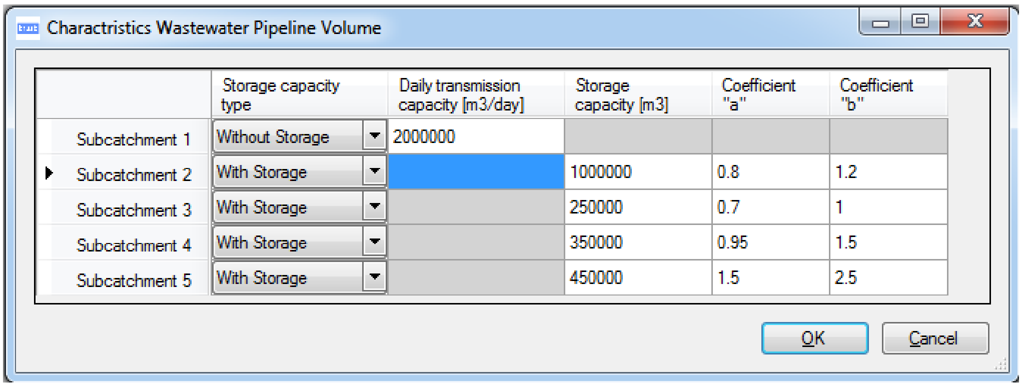


Figure 4 20: Specifications of two types of sewer system storage

The third section of the ‘Asset’ tab shown in Figure 4 21 provides specifications of WWTWs. For each WWTW, the user defines basic specifications plus chemicals, contaminant removal and resource recovery. To define contaminant removals in a WWTW, the user needs to define the contaminants of interest in the **Tools>>Option>>Contaminant** tab beforehand.

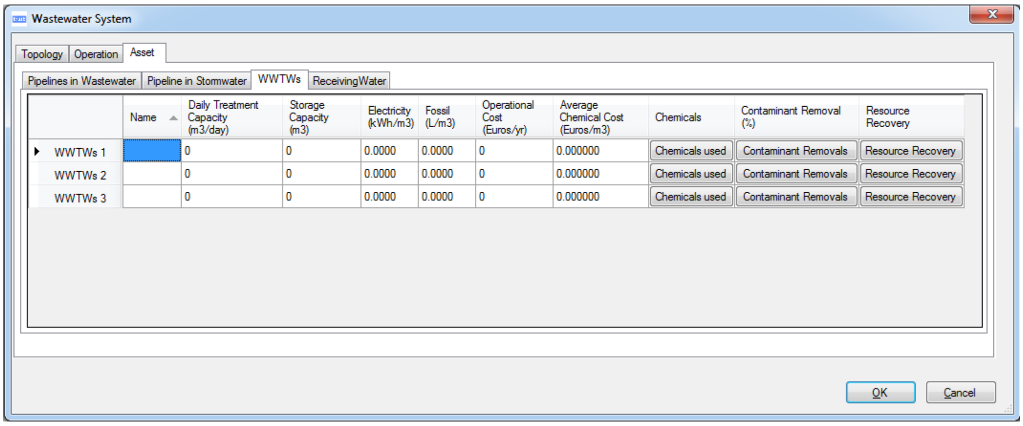


Figure 4 21: Specifications of WWTWs in the 'Asset' tab

4.2.4. Time Series

The time series defined in WaterMet^2 as shown in Figure 4 22 are: 'Inflows', 'Weather' and 'Distribution Network Pipelines'. The first two times series (i.e. 'Inflows', 'Weather') are necessary for running a simulation in a WaterMet^2 model but the third one is necessary if pipeline rehabilitation is activated in 'Option' form.

The relevant form for defining the time series appears by clicking **Input Data>>Import Time Series** button. The 'Time Series Editor' form contains the aforementioned three tabs (Figure 4 22). In all three tabs, there are three buttons for managing time series data: 'Fill Table', 'Browse' and 'Delete'. If the time series data have been defined in an existing WaterMet^2 model, by clicking 'Fill Table' button, they are populated in a table below the buttons. Clicking 'Delete' button will permanently delete the time series data associated with that tab. To define new time series data the user needs to click the 'Browse' button and then select the file of time series of interest.

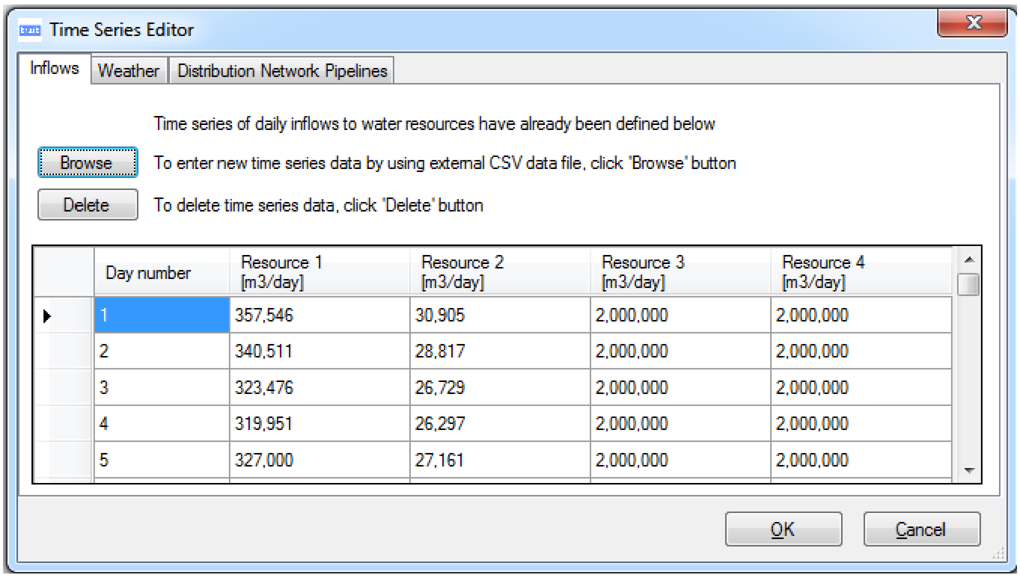


Figure 4 22: 'Inflow' tab in 'Time Series Editor' form

WaterMet² receives all the time series data as .CSV files. A sample of the format of the inflow time series data is presented in Figure 4 23. When receiving the CSV file of inflow time series, WaterMet² checks if the number of columns (i.e. number of resources) corresponds with the number of resources defined in 'Water Supply' form. If the numbers are not equal, the user will need to correct it and insert again.

For all CSV files, except for the cells in which letters are allowed, using letters for other cells is not allowed. Otherwise, the input data are not received successfully and an error message will notify the user. For a successful data entry, an information message of successfully receiving the data will be shown.

Resource1	Resource2	Resource3	Resource4	Resource5	Resource6	Resource7	Resource8
357545.8622	30905.24208	2000000	2000000	343447.9426	29177.22069	2000000	2000000
340510.8762	28817.21626	2000000	2000000	356371.0355	30761.24029	2000000	2000000
323475.8901	26729.19043	2000000	2000000	349909.4891	29969.2305	2000000	2000000
319951.4101	26297.18508	2000000	2000000	332287.0897	27809.20378	2000000	2000000
327000.3699	27161.19576	2000000	2000000	310552.7972	25145.17083	2000000	2000000
327000.3699	27161.19576	2000000	2000000	310552.7972	25145.17083	2000000	2000000
315252.1037	25721.17796	2000000	2000000	309377.9705	25001.16904	2000000	2000000

Figure 4 23: Format of inflow time series data in a .CSV file

The CSV file of the weather data must follow the format of a sample shown in Figure 4 24. In this file, the first line is header allocated for any explanatory text which is ignored by WaterMet² when reading. The first column is also a date for the time of interest. This column is also for descriptive purposes of the user although it will be shown in the Table of 'Time

Series Editor' form. The cells in the fourth column (i.e. Precipitation type) must be precisely specified as one of the four types (especially the upper and lower case of the letters): 'Rain', 'Snow', 'Sleet' and 'Not'. Also, when this file is chosen through the 'Browse' button on the 'Weather' tab, WaterMet^2 checks if the number of columns in the CSV file corresponds to the number of expected columns (i.e. 11). In the case of inconsistency, an error message will be shown for which the user needs to correct the input file and try it again.

Date	Precipitation [mm]	Snow depth [cm]	Precipitation type	Mean temperature	Minimum temperature	Maximum temperature	Average wind speed (main observations) [m/s]	Hours of sunshine	Mean relative humidity	Vapour pressure [hPa]
1011981	1	10	Rain	-0.1	-2.8	3	1.7	3.2	54	3.2
2011981	0	10	Not	-2.8	-4.7	1.2	1.6	3.1	50	2.6
3011981	0	10	Not	-5.1	-7.4	-3.8	4.3	4.8	57	2.5
4011981	0	10	Not	-6.6	-7	-4	2.1	0	73	2.8
5011981	0.7	11	Snow	-12.7	-14.5	-6.1	1.2	0	71	1.7
6011981	0	11	Not	-15.3	-17.3	-12.7	0.8	4.9	77	1.4
7011981	0	11	Not	-8	-15.8	-5.7	5.3	4.8	36	1.3
8011981	6.4	14	Snow	-1	-10	2.2	2.6	0	86	5.2
9011981	0.1	14	Rain	0.6	-2.4	3.5	0.3	1	84	5.8
10011981	0	14	Not	-3.1	-8.6	2.1	3.1	5.6	58	2.6
11011981	0	14	Not	-4.6	-6.6	-2.2	2.4	0.3	75	3.4
12011981	0	14	Not	0.9	-3	2.7	2.8	0	71	4.6
13011981	0	14	Snow	-5.1	-9.2	-0.6	0.2	2.9	52	2.4
14011981	4.4	19	Snow	-3.8	-8.9	-2.8	2.2	0	94	4.5
15011981	5	24	Snow	-3.3	-6.1	-1.2	2.8	0	51	2.6
16011981	0	21	Not	-0.7	-7.6	1.2	6.7	0	35	2.3
17011981	0	21	Not	-5.1	-8.4	-1.9	4.3	3.6	48	2.1
18011981	0	21	Not	-9.9	-11.5	-5.5	3.3	0	64	1.9

Figure 4 24: Format of weather data in a .CSV file

Format of a .CSV file for distribution pipeline time series data is shown as an example in Figure 4 25. The pipeline time series data are provided for each subcatchment separately. Four main features of pipelines provided in each subcatchment are: material type, length, diameter and age. The relevant units for length, diameter and age are metre, millimetre and year, respectively. The format type of this table must strictly follow specific format otherwise WaterMet^2 is unable to read it and an appropriate message is shown for correction and re-try. This format is as follows:

- The first row defines the subcatchment number (for instance the pipeline specifications shown Figure 4 25 are represented for three subcatchments). The number of subcatchment (digit) must be repeated for all four column of each subcatchment.
- The second row is the column header explaining the types of pipeline data. The order of columns for pipeline specifications of each subcatchment must be as follows: material type, length, diameter and age. This order must be repeated for all subcatchments.
- The next rows describe the pipeline database. These cells must strictly follow specific format: (1) material type need to be precisely corresponded with one of eight material types (especially the upper and lower case of the letters) supported by WaterMet^2: Concrete, Ductile iron, Grey cast iron, Mild steel, GRP, PE, PVC,(2) other columns must be numeric and no letter is allowed.

1	1	1	1	2	2	2	2	3	3	3	3
Material type	Length [m]	Diameter [mm]	Age [year]	Material type	Length [m]	Diameter [mm]	Age [year]	Material type	Length [m]	Diameter [mm]	Age [year]
Ductile iron	35.72	150	26	Ductile iron	47.62	150	42	Ductile iron	25.59	150	31
Ductile iron	15.7	150	26	Grey cast iron	54.15	125	71	Ductile iron	28.03	200	41
Grey cast iron	39.85	150	47	Grey cast iron	61.87	125	61	Grey cast iron	24.88	200	53
Ductile iron	39.2	150	39	Ductile iron	65.27	400	35	Ductile iron	33.06	200	41
Ductile iron	26.99	150	39	Grey cast iron	58.73	125	80	Ductile iron	77.67	200	41
Ductile iron	37.8	150	23	Ductile iron	63.27	400	35	Ductile iron	19.59	150	31
Ductile iron	36.74	150	42	Grey cast iron	60	150	80	Ductile iron	19.02	150	31
Ductile iron	33.76	150	42	Grey cast iron	68.55	150	53	Ductile iron	38.75	150	31
Ductile iron	36.44	150	42	Ductile iron	22.34	400	35	Ductile iron	11.85	150	31
Ductile iron	18.73	150	42	Ductile iron	70.85	150	35	Ductile iron	23.08	200	31
Ductile iron	26.39	150	42	Ductile iron	36.75	150	35	Ductile iron	71.98	150	35

Figure 4 25: Format of Distribution Pipeline time series data in a .CSV file

4.2.5. Options

Some of the general assumptions in a WaterMet^2 model can be set in the 'Option' form. This form can be accessed through clicking either **Tools>>Options** button or 'Option' button in the left hand pane. This form comprises nine tabs each of which sets some general or specific assumptions in a WaterMet^2 model. For filling each of these tabs, a 'Default Values' button would help to quickly populate default values for all constants and parameters. **All tabs default values** button can also fill out all the nine tabs instantly.

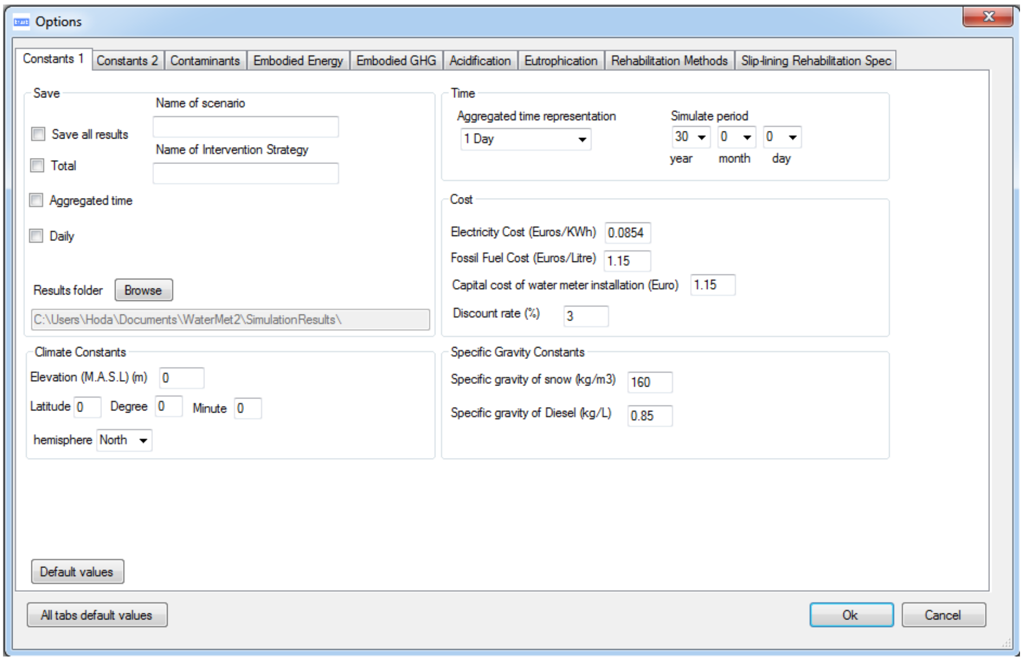


Figure 4 26: Constant in the 'Option' form

These tabs along with a brief description of their performance are as follows:

- **Constant 1** (Figure 4 26), which contains constants and settings for different parts of a WaterMet^2 model including

  -*Save*: it provides how and where results are saved after running a simulation.

  -*Time*: it specifies duration of a simulation run

  -*Cost*: it specifies cost of electricity and fossil fuel (diesel) and inflation rate

  -*Climate constants*: it is used in rainfall-runoff modelling for calculating evaporation

  -*Specific gravity (SG) constants*: SG for snow and diesel which will be used for rainfall-runoff modelling and all calculations relevant to diesel, respectively.

- **Constant 2** which contains the coefficients for all water demand categories including

  -Percentage conversion from water to wastewater

  -Percentage coefficients for water consumption by appliances and fittings

  -Energy consumptions by appliances and fittings.

- **Contaminant** in which the user defines any number of contaminants of interest up to 10 and specifies their concentration as EMC (event mean concentration) for all water demand categories and different types of surface area.
- **Embodied Energy, Embodied GHG emission, Acidification and Eutrophication** which are specified for four groups: chemicals, materials and electricity & fuels and by-products.
- **Rehabilitation Methods** which specifies share, cost and GHG emissions of four rehabilitation methods supported by WaterMet^2: Lining with Polyurethane (PU), Slip-lining with PE pipe, Pipe cracking+ lining and Rebuilding with ductile iron pipe. Note that the cost and associated GHG emissions are specified relative the second method (i.e. Slip-lining with PE pipe) and the detailed costs and GHG emissions for this method is specified in the next tab.
- **Slip lining Rehabilitation Specification** which determines the cost and GHG emissions for three groups of pipe diameter: less than 249 mm, between 250 and 499 mm, and greater than 500 mm.

4.2.6. Water Resource Recovery

Modelling water resource recovery in WaterMet^{2}requires setting parameters in two steps: (1) allocation of water recovery from to different water demand categories; (2) specifying decentralised/centralised recycling water. Each of these steps is described in the following. If either of the two steps is incomplete, water resource recovery might not be working in the WaterMet^2 model.

Water Recovery Allocation

This step requires allocation of recycling water from the sources of water recovery for each water demand category is determined (Figure 4 27). There are two sources of water recovery: RWH and GWR schemes. Water demand categories are: toilet, dish washer, hand basin, kitchen sink, shower, washing machine, industrial and irrigation. The Water Recovery Allocation form can be accessed through clicking **Input Data>>Water Resource Recovery>>Water Recovery Allocation** button.

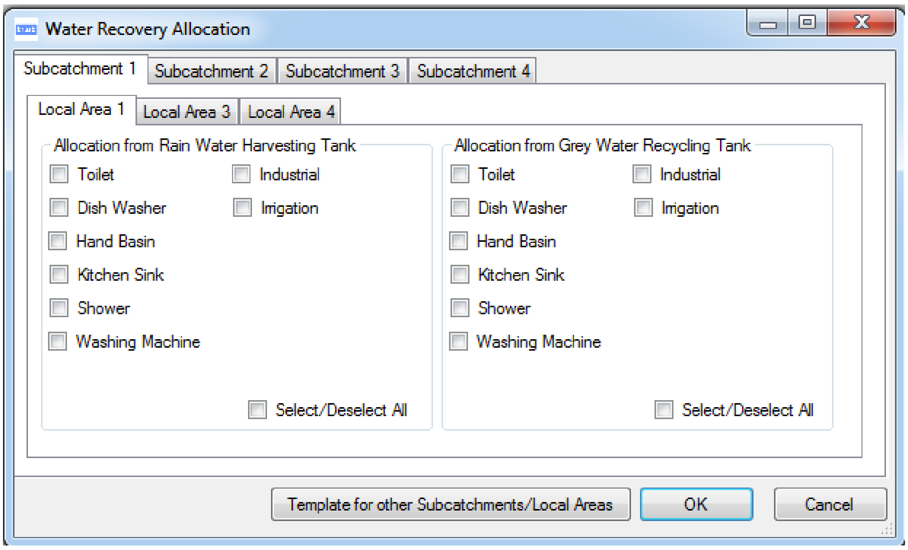


Figure 4 27: 'Water Recovery Allocation' form

Specifying recycling water

In the second step, water recycling schemes need to be defined and their features are specified by the user. Water recycling schemes are: RHW and GWR schemes at both levels of local area and subcatchment. Once the storage capacity of these systems is specified, other features of the system are activated and can be specified by the user. The required characteristics are filled out in four parts: specifications of the recycling system, sources and sinks of water flow, place of consumption for stored/treated water and contaminants removal. Note that contaminants need to be defined in advance in the **Option** form.

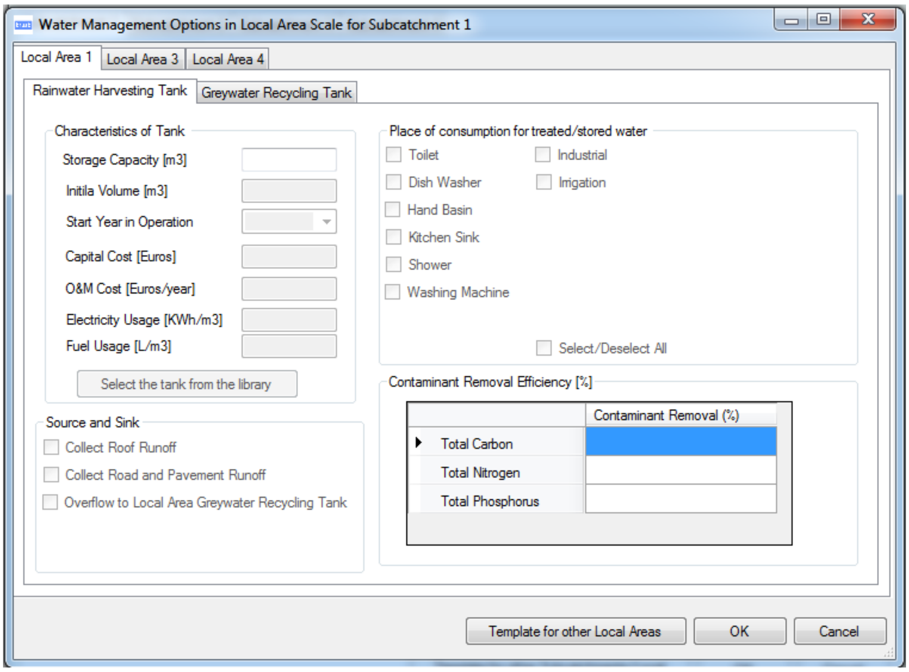


Figure 4 28: Water Management Options form for RWH tank at local area level

4.3. Running a Simulation

After setting all the required parameters, the WaterMet² model will be ready for simulation. There are three ways to run a simulation in WaterMet²: (1) by clicking **Analysis>>Run Simulation** button; (2) clicking on  icon on the Toolbar; (3) clicking F5 button on the keyboard. Figure 4 29 shows a typical window representing simulation in progress in WaterMet². If the program successfully finishes, an information message (e.g. Figure 4 30) representing a successful simulation and its runtime is shown.

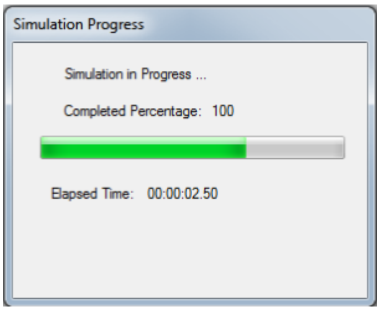


Figure 4 29: Simulation progress form in WaterMet^2

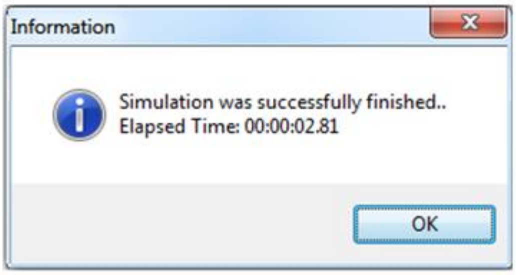


Figure 4 30: Message for successful finishing of WaterMet^2 simulation run

4.4. Results Forms

WaterMet^2 reports results either within the interface or via .csv files. Setting the results through saving in files is carried out by the 'Constant 1' tab in 'Option' form. Representation of the results through the interface is carried as either tabular or graphical form. Either of these two can be accessed in WaterMet^2 through **Report>>Graph** menu or 'Table' menu. Alternatively, there are two shortcuts (i.e. and icons) in the Toolbar to have a quick access to graph and table options, respectively.

Before representation of the results through the WaterMet^2 interface, a group of KPIs of interest must be defined and managed by the form shown in Figure 4 31. More specifically, this form provides an interface to define some KPIs of interest for either graphical or tabular representation. Also, some previously saved time series of KPIs are retrieved in this form for representation. This form consists of five parts:

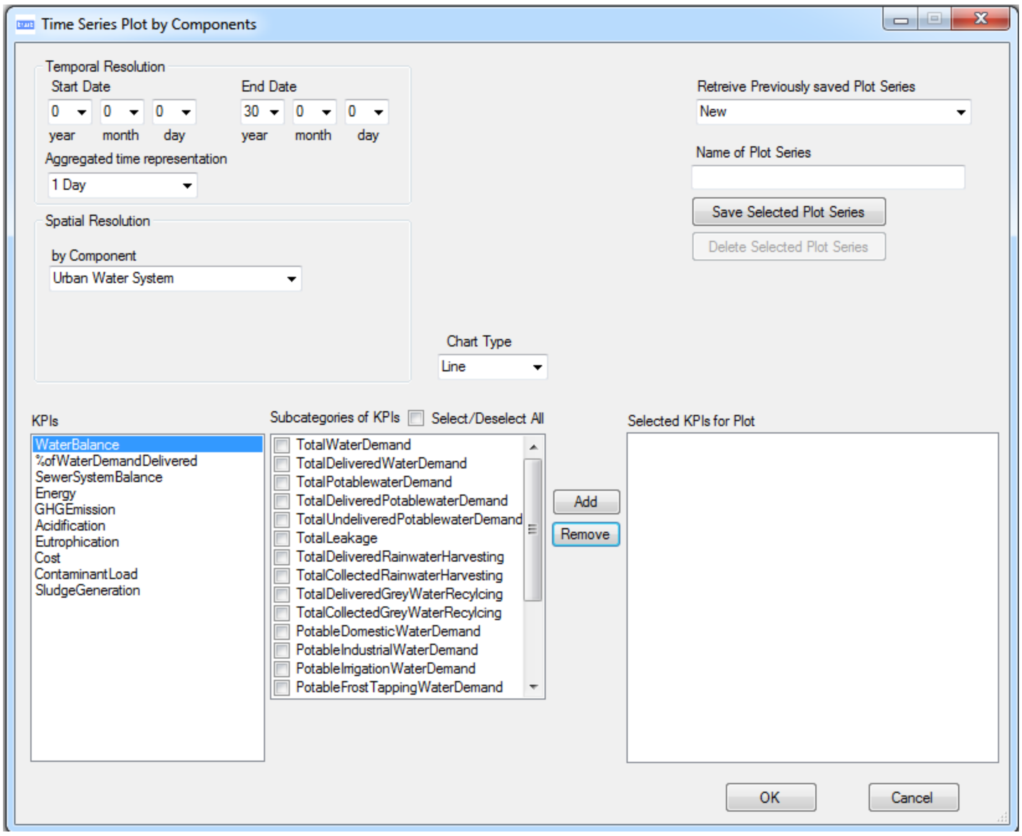


Figure 4 31: Options for representation of KPIs

- **Spatial resolution** which specifies the components of interest.
- **Temporal resolution** containing start, end dates and aggregated time for KPIs representation.
- **KPIs** which contain a list of available KPIs which can be quantified by WaterMet^2.
- **Retrieve previously saved sets of KPIs or save selected KPIs**
- **Selected KPIs for plot**

Spatial resolution consists of “urban water system”, “water resource”, “water supply conduits”, “WTWs”, “trunk mains”, “service reservoirs”, “distribution mains”, “subcatchments”, “sewer systems”, “WWTWs”, “receiving water”, “subcatchment RWH tank”, “subcatchment GWR tank”, “local area RWH tank”, “local area GWR tank”. For all components, the user needs to specify either component number or “total” representing sum of the KPI values for all components of the same type. Also, Table 4 1 and 4 2 presents KPIs of UWS components calculated by WaterMet^2.

Table 4 1 KPIs for a number of UWS components

No	WATER RESOURCES	WATER SUPPLY CONDUITS	WTWS	TRUNK MAINS	SERVICE RESERVOIRS	DISTRIBUTION MAINS
1	Inflow	Inflow	Inflow	Inflow	Inflow	Inflow
2	Volume	Leakage	Loss	Leakage	Volume	Leakage
3	Loss	Delivered Outflow	Delivered Outflow	Delivered Outflow	Loss	Delivered Outflow
4	Delivered Outflow	Undelivered Outflow (Lack of Inflow)	Undelivered Outflow (Lack of Inflow)	Undelivered Outflow (Lack of Inflow)	Delivered Outflow	Undelivered Outflow (Lack of Inflow)
5	Undelivered Outflow	Undelivered Outflow (Exceeding Capacity)	Undelivered Outflow (Exceeding Capacity)	Undelivered Outflow (Exceeding Capacity)	Undelivered Outflow	Undelivered Outflow (Exceeding Capacity)
6	Overflow	Total Energy	Overflow	Total Energy	Overflow	Total Energy
7	Total Energy	Electricity Energy	Total Energy	Electricity Energy	Total Energy	Electricity Energy
8	Electricity Energy	Fossil Fuel Energy	Electricity Energy	Fossil Fuel Energy	Electricity Energy	Fossil Fuel Energy
9	Fossil Fuel Energy	Embodied Energy	Fossil Fuel Energy	Embodied Energy	Fossil Fuel Energy	Embodied Energy
10	Embodied Energy	Total GHG Emission	Embodied Energy	Total GHG Emission	Embodied Energy	Total GHG Emission
11	Total GHG Emission	Electricity GHG Emission	Total GHG Emission	Electricity GHG Emission	Total GHG Emission	Electricity GHG Emission
12	Electricity GHG Emission	Fossil Fuel GHG Emission	Electricity GHG Emission	Fossil Fuel GHG Emission	Electricity GHG Emission	Fossil Fuel GHGE mission
13	Fossil Fuel GHG Emission	Embodied GHG Emission	Fossil Fuel GHG Emission	Embodied GHG Emission	Fossil Fuel GHG Emission	Embodied GHG Emission
14	Embodied GHG Emission	Acidification	Embodied GHG Emission	Acidification	Embodied GHG Emission	Acidification
15	Acidification	Eutrophication	Acidification	Eutrophication	Acidification	Eutrophication
16	Eutrophicatio n	Total Cost	Eutrophication	Total Cost	Eutrophicatio n	Total Cost
17	Total Cost	Capital Cost	Total Cost	Capital Cost	Total Cost	Capital Cost
18	Capital Cost	Operational Cost	Capital Cost	Operational Cost	Capital Cost	Operational Cost
19	Operational Cost	Energy Generation	Operational Cost		Operational Cost	
20			Sludge Generation			

Table 4 2 KPIs for a number of UWS components (subcatchments, sewer systems and WWTWs)

No	SUBCATCHMENTS	SEWER SYSTEMS	WWTWS
1	Total Water Demand	Storm water Inflow	Inflow
2	Total Delivered Water Demand	Excess Storm water	Volume
3	Total Potable water Demand	Storm water Volume	Loss
4	Total Delivered Potable water Demand	Sanitary Sewage Inflow	Treated Outflow
5	Total Undelivered Potable water Demand	Excess Wastewater	Untreated Outflow (CSO)
6	Total Delivered Rainwater Harvesting	Wastewater Volume	Total Energy
7	Total Collected Rainwater Harvesting	STO	Electricity Energy
8	Total Delivered Grey Water Recycling	CSO	Fossil Fuel Energy
9	Total Collected Grey Water Recycling	Total Energy	Embodied Energy
10	Potable Domestic Water Demand	Electricity Energy	Total GHG Emission
11	Potable Industrial Water Demand	Fossil Fuel Energy	Electricity GHG Emission
12	Potable Irrigation Water Demand	Total GHG Emission	Fossil Fuel GHG Emission
13	Potable Frost Tapping Water Demand	Electricity GHG Emission	Embodied GHG Emission
14	Potable Unregistered Water Demand	Fossil Fuel GHG Emission	Acidification
15	Delivered RHW for Domestic Water Demand	Acidification	Eutrophication
16	Delivered RHW for Industrial Water Demand	Eutrophication	Total Cost
17	Delivered RHW for Irrigation Water Demand	Total Cost	Capital Cost
18	Delivered GWR for Domestic Water Demand	Capital Cost	Operational Cost
19	Delivered GWR for Industrial Water Demand	Operational Cost	Contaminant Load
20	Delivered GWR for Irrigation Water Demand	Contaminant Load	Inflow Contaminant Load
21	% of Water Demand Delivered	Inflow Sewer System Contaminant Load	Outflow Contaminant Load
22	Total Energy	Inflow Storm Drainage System Contaminant Load	Overflow Contaminant Load
23	Electricity Energy	Excess wastewater Contaminant Load	Sludge Generation
24	Fossil Fuel Energy	Excess Storm water Contaminant Load	Resource Recovery
25	Embodied Energy	Outflow Sewer System Contaminant Load	Biogas generated
26	Total GHG Emission	Outflow Storm Drainage System Contaminant Load	ammonium nitrate generated
27	Electricity GHG Emission	CSO Contaminant Load	Single superphosphate generated
28	Fossil Fuel GHG Emission	STO Contaminant Load	Urea generated
29	Embodied GHG Emission		

30	Acidification		
31	Eutrophication		
32	Total Cost		
33	Capital Cost		
34	Operational Cost		

Graph Representation

After setting all the parameters in the abovementioned form, the user is recommended to click **save Selected Plot Series** button in order to avoid missing the settings of the KPIs. If more than one set of KPIs is selected for graph representations, the relevant graphs are shown in different tabs (see Figure 4 32). For instance, monthly variations of four types of GHG emissions (i.e. electricity, fossil fuel, embodied energy and total amount) are shown in this figure as Line Chart. As can be seen here, fossil fuel consumption (green colour) is almost negligible compared to the GHG emissions resulted from electricity (red colour) and embodied (purple colour) energies. Other than representation as Line Chart, the user can select representation of the variations as Bar Chart by selecting it in the dropdown combo box. Many capabilities in a normal graph are supported here through right click on the graph screen. There are two types for the charts in graphical representation: bar chart and line chart. Bar char can be useful especially when the aggregated time step is large enough (e.g. 1 year) in order to distinguish different values.

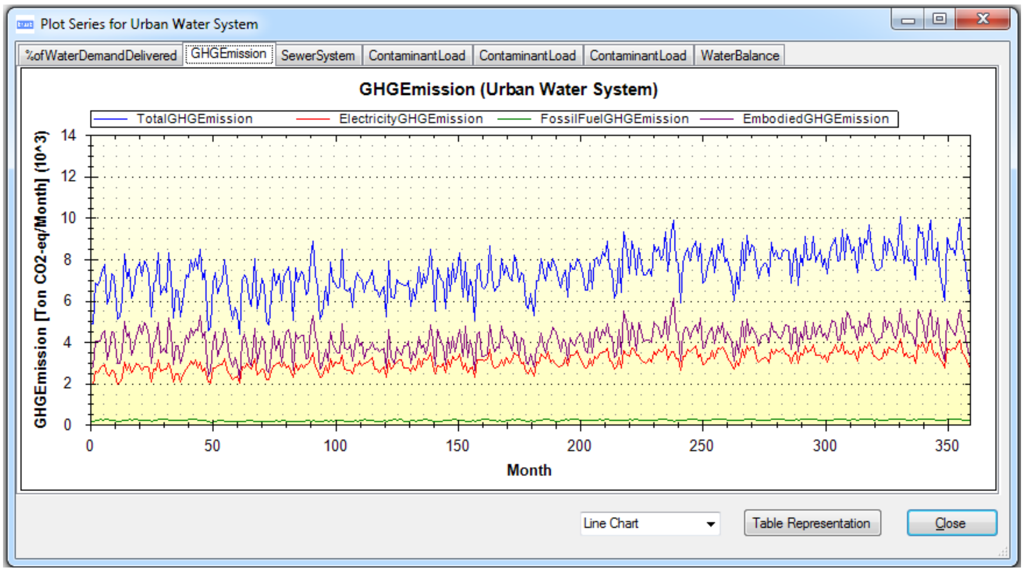
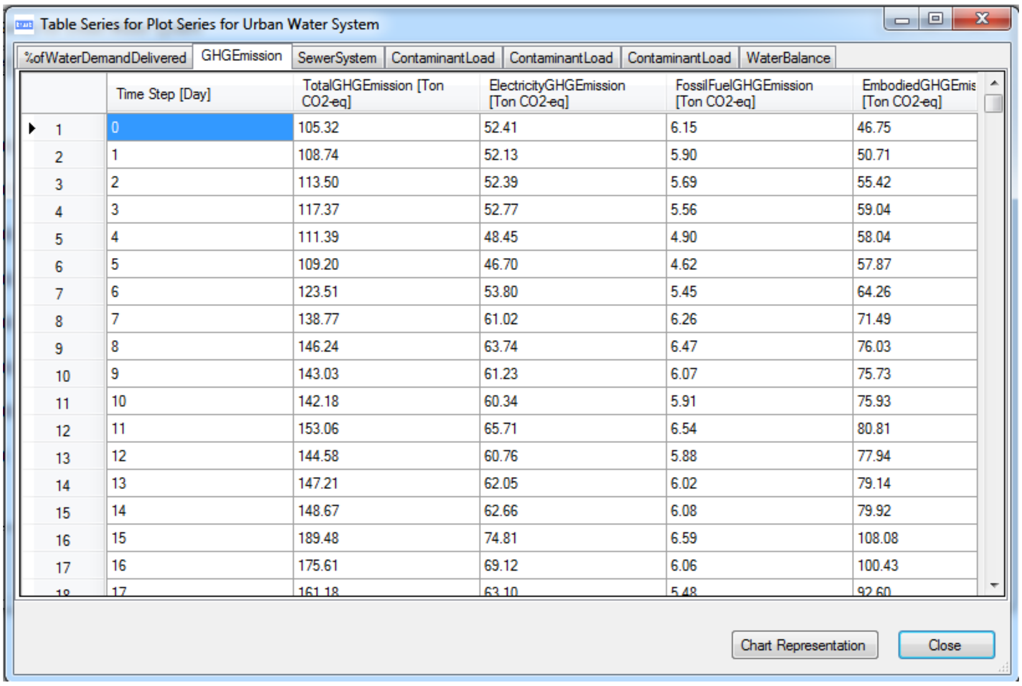


Figure 4 32: An example of graph representation form in WaterMet²

4.4.2. Table Representation

In the above form, the user can simply switch from the graphical representation to tabular representation which is shown in Figure 4 33. This switch can also be done in the tabular representation by clicking 'Chart Representation' button. One of the quickest and most efficient ways to save the result in a format other than defined representations is to select the table data of interest and copy and paste it in other programs such as MS Excel. To select all tabular data in a table, the user needs to click on top and left cell by which all the cells are selected.



	Time Step [Day]	TotalGHGEmission [Ton CO2-eq]	ElectricityGHGEmission [Ton CO2-eq]	FossilFuelGHGEmission [Ton CO2-eq]	EmbodiedGHGEmis [Ton CO2-eq]
1	0	105.32	52.41	6.15	46.75
2	1	108.74	52.13	5.90	50.71
3	2	113.50	52.39	5.69	55.42
4	3	117.37	52.77	5.56	59.04
5	4	111.39	48.45	4.90	58.04
6	5	109.20	46.70	4.62	57.87
7	6	123.51	53.80	5.45	64.26
8	7	138.77	61.02	6.26	71.49
9	8	146.24	63.74	6.47	76.03
10	9	143.03	61.23	6.07	75.73
11	10	142.18	60.34	5.91	75.93
12	11	153.06	65.71	6.54	80.81
13	12	144.58	60.76	5.88	77.94
14	13	147.21	62.05	6.02	79.14
15	14	148.67	62.66	6.08	79.92
16	15	189.48	74.81	6.59	108.08
17	16	175.61	69.12	6.06	100.43
18	17	161.18	63.10	5.48	92.60

Figure 4 33: An example of tabular representation form in WaterMet²

4.5. WaterMet²Toolkit

Most of practitioners are expected to use the standalone version of the WaterMet² software tool (as described above). More advanced users are provided also with the Toolkit described briefly in this section. The Toolkit is essentially a DLL library of different functions that enable controlling the WaterMet² tool from other applications written by advanced users, e.g. for the purpose of UWS optimisation and/or risk and uncertainty analysis.

The source code of WaterMet² simulation model was written in C# Visual Studio .NET framework which is encapsulated into a .NET DLL file called WaterMet2.dll. Advanced users are able to communicate with key components of this 'global data' file through a series of functions known as 'Toolkit functions' instead of becoming involved in the complicated structure of the source code written in one specific programming language. These functions are written in a standard format which can be easily be called by many other programming languages (e.g. MATLAB and other .NET Framework languages such as VB and C++). The WaterMet^2 toolkit functions have also been encapsulated into a .NET DLL file called Toolkit.dll. These DLL files are freely available for advanced users and can be accessible through either upon request from the developers or the TRUST website.

The users of other programming languages (e.g. MATLAB and VB .NET) can add the WaterMet^2 DLLs into their project and then call the toolkit functions to communicate with the key components of the WaterMet^2 simulation model. Thus, the users can change the WaterMet^2 model according to their own settings and retrieve the required data within the simulation whenever needed. This can be very useful for many applications and analyses such as optimisation and risk analysis. In the appendix D, an example of using toolkit functions is given using three programming languages. This method is also employed by the current graphical user interface of WaterMet^2 tool to communicate the global data which includes all the functions related to the Watermet^2 simulation model.

Note that the WaterMet^2 toolkit is a set of around 100 functions which is able to open and save the input file; then set and retrieve the input data, run the WaterMet^2 simulation model and finally retrieve the results of the simulation. More details of these functions along with their own arguments can be found in Behzadian and Kapelan (2014).

5. Case Study

This chapter illustrates the model design concept based on real UWS data and how to construct and calibrate a new WaterMet^2 model using the software tool described in the previous chapter. Once this is done, the chapter demonstrates how to run a simulation model, retrieve and analyse the resulting KPI values. At the end, several examples are provided on how the built tool can be used to model different interventions.

The application of the WaterMet^2 software tool is demonstrated here through the simulation of the UWS of the reference city (i.e. Oslo city in Norway) in WaterMet^2. The UWS WaterMet^2 model is also evaluated for a period of 30 years starting from 2011 with a daily time step. The preparation of input data requirements is described in a step-by-step process within which it is demonstrated how they are collected and arranged for modelling in WaterMet^2. Also, the case study explains how the result of the simulation can be shown and analysed in different ways. In the rest, the problem description is first presented in which the layout and components of the case study is described in detail. The following section describes populating the relevant input data forms in WaterMet^2. Different ways of presenting and extracting key performance indicators as WaterMet^2 results are then described. Finally, different individual intervention options are analysed in the WaterMet^2 model. Note that this chapter focuses on how the user can apply of the WaterMet^2 model in a real-life case study to retrieve the KPIs of interest. Further analysis from the application of WaterMet^2 as a metabolism based model for long-term planning and management of the UWS can be done based on multi-criteria decision analysis the KPIs obtained from the WaterMet^2 model. An example of this analysis for long-term UWS planning was done in Oslo case study report (Behzadian and Kapelan 2013) in which resulting KPIs of the WaterMet^2 model were combined with multi-criteria decision analysis. Some other specific applications of WaterMet^2 to the UWS can be found in the relevant publications such as Behzadian *et al.* (2014a) and Behzadian *et al.* (2014b).

Note that the data used in this chapter have been adjusted for Oslo/Norway. They are not pure Ecoinvent life cycle inventory data. However, any other utility using the model, may wish to adjust it back to their city/country. They would then have to take recourse to some environmental dataset from some database. They may have a license to use Ecoinvent data. If they do not, they would need to obtain one, or resort to other means of getting the environmental data. This is just information which would need to be given to anyone who would be using the model later on.

5.1. The UWS Description

Many cities are already facing challenges due to population growth, increasing urbanization and ageing infrastructure. These factors are expected to impose significant strains on their UWSs In order to define these challenges and the conceptual framework for WaterMet^2 model, the Oslo city's UWS has been used as a reference model. A brief description of the existing UWS, its entities and significant relations among the entities is outlined here (Oslo VAV, 2012).

Figure 5-1 shows the main components of the UWS comprises two mains part of water supply and wastewater subsystems. The main components of the water supply subsystem are water resources, water supply conduits, WTWs, trunk mains, distribution mains and subcatchments. The existing UWS, as shown in this figure, is fed by two main raw water resources each connected to a WTW which provides fresh water for Oslo (VAV, 2011b). The pipelines in the distribution network, connecting the single subcatchment to the two upstream WTWs, are split into two parts. Both of the surface water resources, on which the city relies, are of limited capacity and inflow. In addition, the treatment capacity of the current WTWs in Oslo is limited and cannot meet the increasing water demand in the future.

The main components of wastewater subsystem are sewer systems, WWTWs and receiving water. The existing sewer system of Oslo city is a mix of combined and separate sewer systems. Two WWTWs collect wastewater from water demand points and storm water from urban rainfall events. Treated wastewater of both WWTWs is discharged into the sea as receiving water.

Input data requirements for modelling the existing UWS in WaterMet^2 are presented in three main subsystems: (1) water supply; (2) water demand; (3) wastewater. The construction of input data and populating the relevant form are explained whenever possible within the description of the available data for each component.

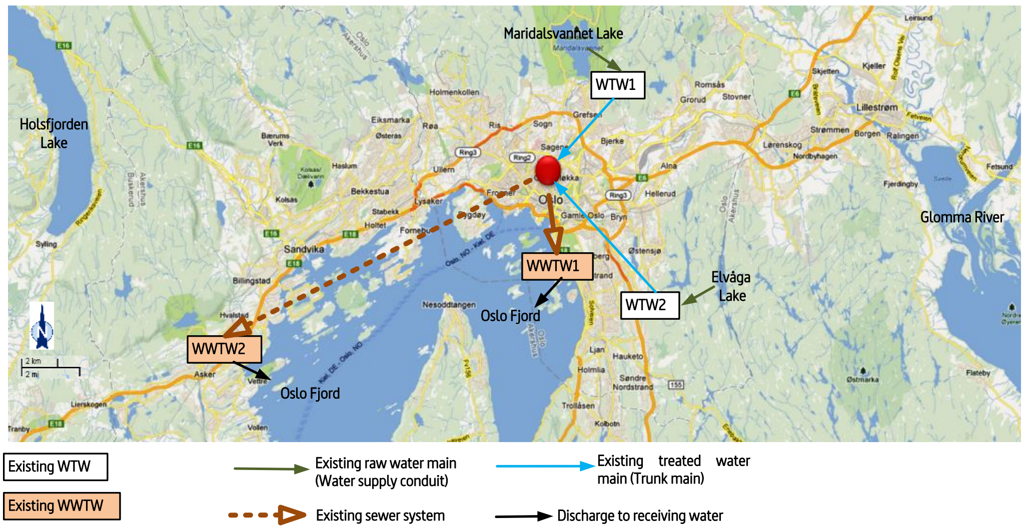


Figure 5 1: Layout of the main components in the UWS for existing conditions (background map from Oslo Google Map (2013)

5.2. Building the UWS WaterMet^2 Model

5.2.1. Water Supply Subsystem

Based on the problem description outlined above, the topology of water supply subsystem can be constructed according to the layout in Figure 5-1. A set of pre-defined forms related to the components of water supply subsystem need to be specified in WaterMet^2. Comparing the components of the Oslo water supply subsystem (WSS) in the figure and those required in WaterMet^2 shows that the WSS has no service reservoir due to the fact that the detailed specifications of the service reservoirs which receive treated water from these two water resources was not available at the time of the modelling. As WaterMet^2 needs to model all the components of the UWS in a sequential manner, in case of data unavailability for any element, dummy elements should be placed in order to ensure connectivity of WaterMet^2 model components. Therefore, without loss of accuracy, it is assumed that there are two dummy service reservoirs prior to distributing water between water demand points.

Figure 5 2 shows the 'Topology' tab ('Water Supply' form) filled-in with data from the case study. The subsequent tab beneath this tab represents how the storage components of the water supply subsystem are linked to each other through the flow routes. Out of three user defined flow routes (i.e. water supply conduit, trunk main and distribution main) in this figure, two distribution mains need to be defined in order to connect the dummy service reservoirs to the single subcatchment. The next step is to complete the specification of these components in other tabs of this form which will be outlined below.

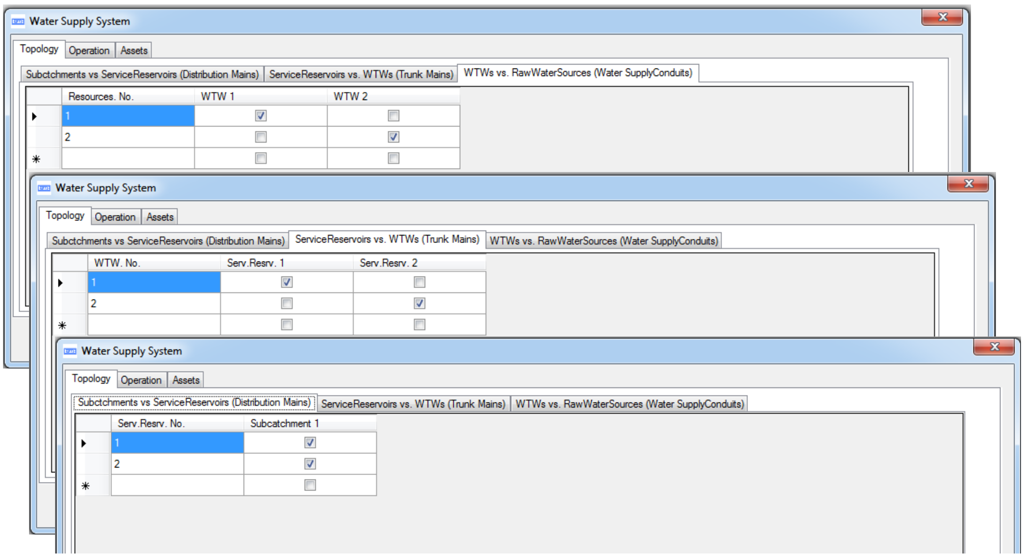


Figure 5 2: Filled 'Topology' form for storage components of the water supply subsystems in WaterMet^2

Raw water resources

There are currently two main raw water resources to supply fresh water to Oslo city- Maridalsvannet Lake, located in the north with 90% supply, and Elvåga Lake, located in the east with 10% supply, (Figure 5-1). These water resources have specific storage capacity but water abstraction for urban water supply is carried out by gravity and hence there is no need for energy consumption. Thus, the specifications of the two water resources in the WSS can be populated in the 'Resources' table under 'Assets' tab of 'Water Supply form' form in waterMet^2 as shown in Figure 5 3. Also the initial volume of these resources is assumed to be half of their storage capacity. Note that, the initial volume can affect the simulation result if the duration of planning horizon is too small.

As the catchment areas of the two existing water resources are limited, the water supply of Oslo city can be affected by the annual water inflows into these water resources. The available data of the water flows for these two sources are the time series of monthly inflows and water withdrawals between 1900 and 2010, which are shown in Figure 5 4 and Figure 5 5 (Oslo VAV, 2012). Note that the minimum environmental water demands of downstream rivers were subtracted from the inflows, and hence, these net inflows are fully assigned to the water supply in Oslo. For the purpose of this case study, time series of the last 30 years (i.e. between period 1981 and 2010) are selected and assumed to be the inflows to service reservoirs over the 30 year planning horizon. Thus, daily time series of inflows into these two resources are constructed from uniformly splitting monthly values and finally entered in the time series of inflows in WaterMet^2 as shown in Figure 5 6.

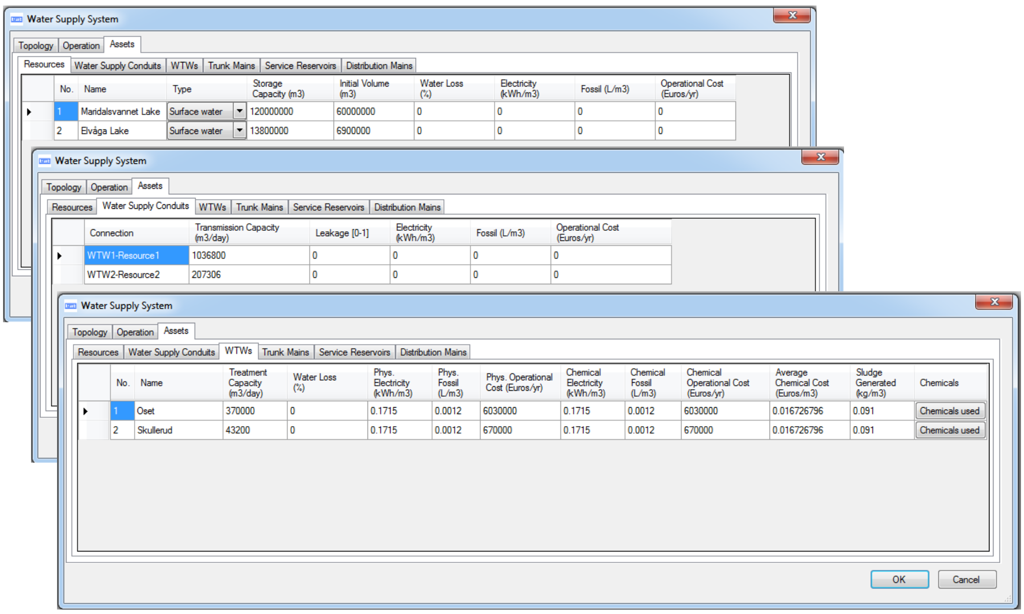


Figure 5 3: Filled 'Assets' tab for resources, conduits and WTWs of the WSS

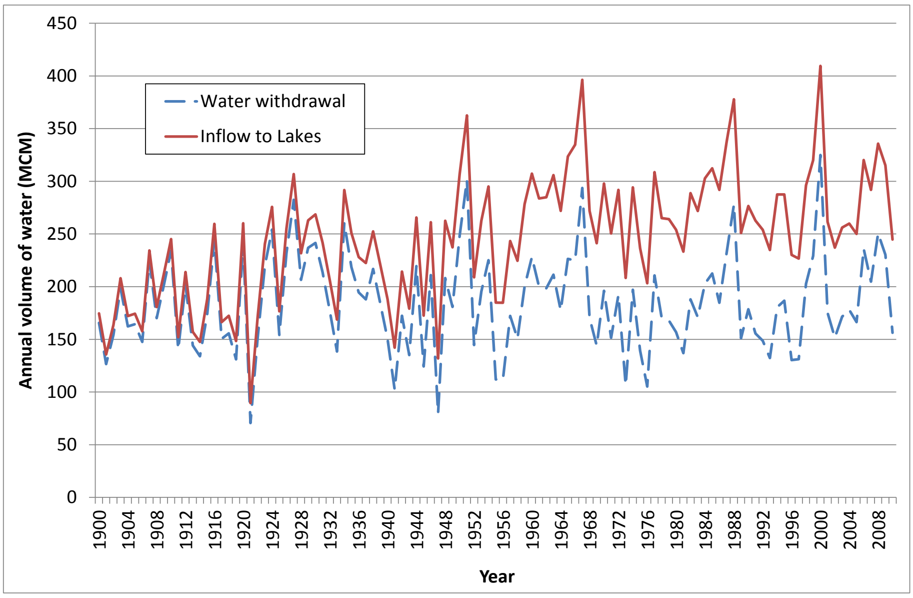


Figure 5 4: Annual volume of water inflows to, and withdrawal from, Maridalsvannet and upstream lakes between 1900 and 2010 (Hem 2012)

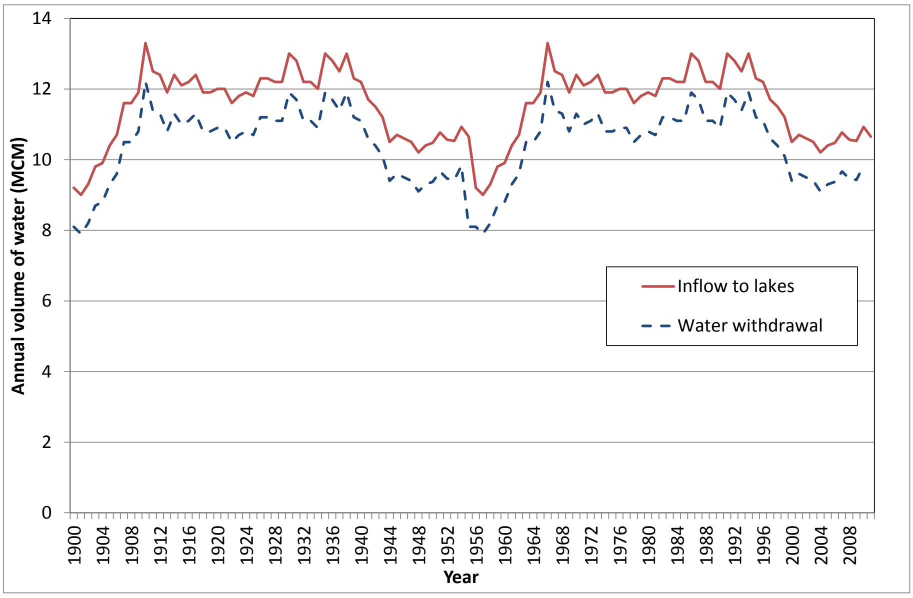


Figure 5 5: Annual volume of water inflows to, and withdrawal from, Elvåga and upstream lakes between 1900 and 2010 (Hem 2012)

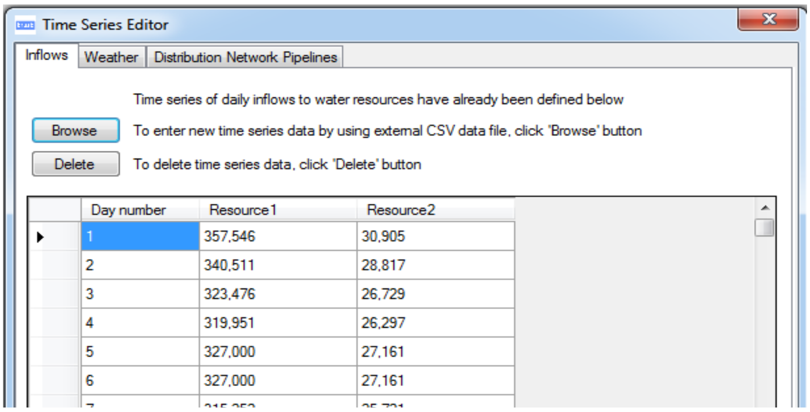


Figure 5 6: Populating daily time series of inflow to the existing water resources of the WSS in WaterMet²

Water supply conduits

Two water supply conduits in the WSS transport raw water from the water resources to the two WTWs (Figure 5 7). The transmission hydraulic capacity of these two conduits (12 and 2.4 m^3/sec) is converted to daily values and populated in 'Water Supply Conduit' table under the 'Asset' tab of '' form in WaterMet² as shown in Figure 5 3. As the raw water flow is transported by gravity, there is no energy required to be filled for these conduits in this table. No leakage and cost is also assumed for them. In addition, as each of the WTWs is fed by only one conduit, the water allocation coefficient of water flow is 100% which is filled in the relevant table under 'Operation' tab of 'Water Supply Subsystem' form (Figure 5 7).

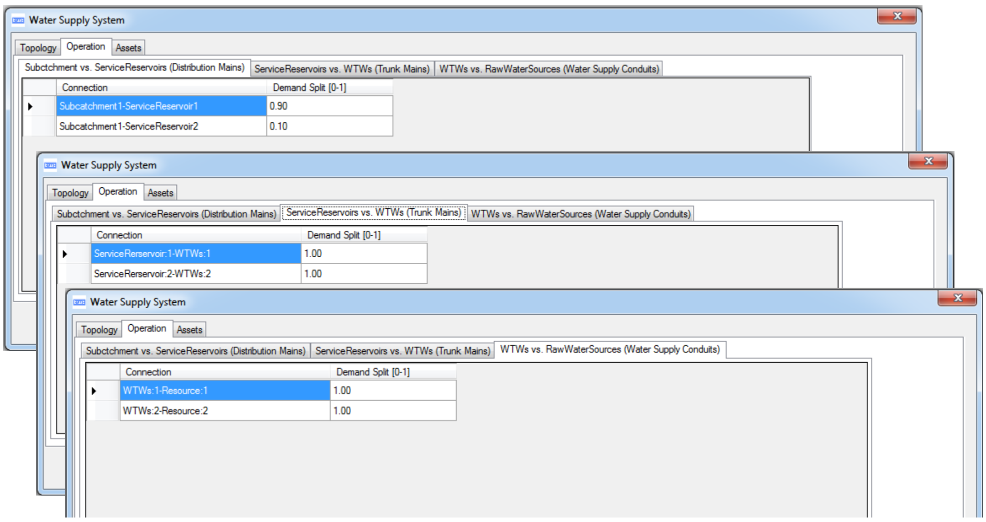


Figure 5 7: Filled 'Operation' tab for conduits, trunk mains and distribution mains of the WSS

WTWs

The two existing WTWs in the WSS (Figure 5 1) which are directly supplied from the existing water resources are: (1) Oset WTWs fed by the Maridalsvannet Lake (located in the northern part of Oslo) and (2) Skullerud WTWs fed by the Elvåga Lake (located in the eastern part of Oslo). The total fix operational cost available for WTWs is split between them proportional to the hydraulic treatment capacity of these WTWs (4.2 and 0.5 m^3/sec). The electricity and fossil fuel consumption per unit volume of water treatment is identical between the WTWs. It is assumed that these values are split up equally between the physical and chemical processes of treatment plant. Therefore, the specifications of the WTWs are filled in the relevant table in the 'Asset' tab under 'Water Supply Subsystem' form (Figure 5 3). The chemicals used for unit volume of water treatment in both WTWs are identical and hence the average chemical cost is also the same. These data are specified in the relevant form defining the chemicals for each WTW (Figure 5 8).

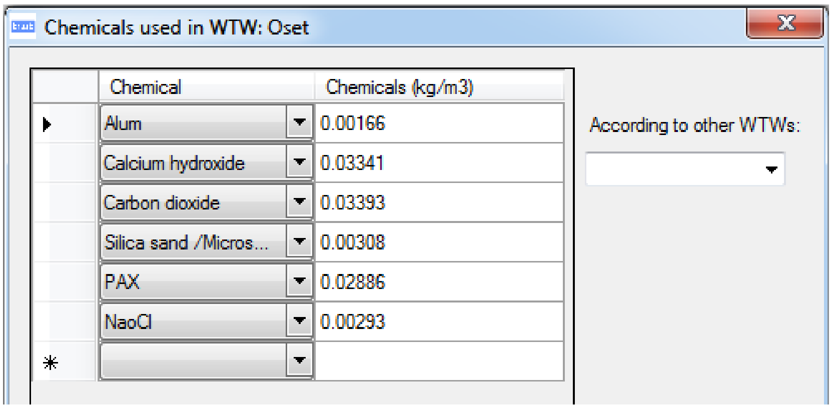


Figure 5 8: Filled 'Chemicals' tab for chemicals used in the WTWs

Trunk mains and Service reservoirs

As shown in Figure 5 1, there are two trunk mains connecting WTWs to service reservoirs in the WSS. The specifications of water flow for these trunk mains cannot be specified due to the two dummy service reservoirs outlined previously. Consequently, some big values need to be set for the specifications of water flow (i.e. daily water transmission or storage capacity) of such elements (i.e. trunk main, service reservoir and distribution mains) such that no water flow limitation (e.g. overflow, lack of capacity) occurs from these elements over the planning horizon. Figure 5 9 shows the relevant forms of the WaterMet^2 model filled by these values which are far bigger than the maximum value of total daily water demands in the reference city. The energy specifications for trunk mains are also considered for distribution mains described in the following. Note that, as each service reservoir is supplied by only one WTW, the percentage split coefficient for each relevant trunk main is 100% (Figure 5 7).

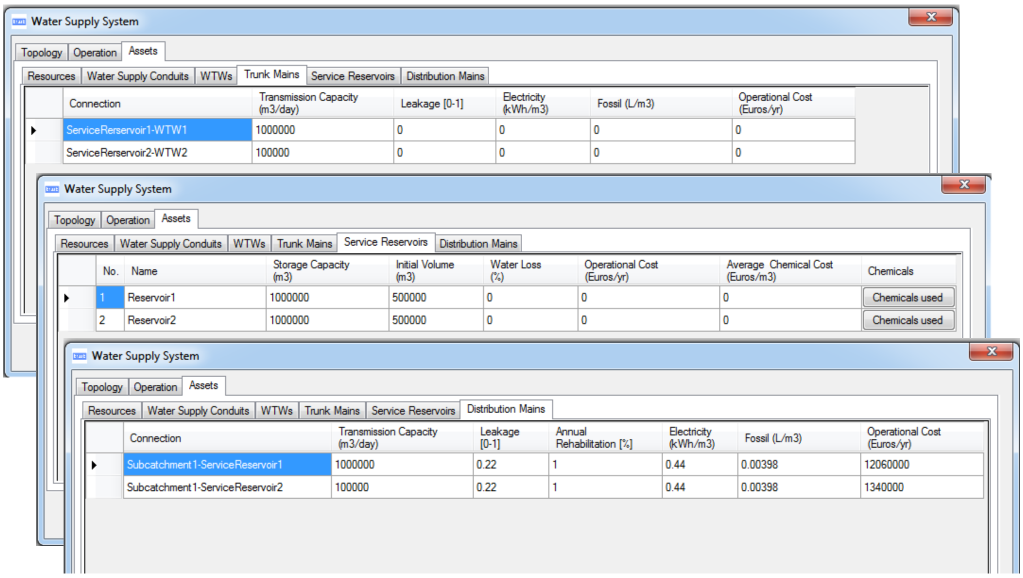


Figure 5 9: Filled 'Assets' tab for trunk mains, service reservoirs and distribution mains of the WSS

Distribution mains

Two distribution mains are required for connecting the single subcatchment of the UWS to the two service reservoirs. Based on the historic water supply in the WSS, it is assumed that 90% of water demand is supplied from Maridalsvannet Lake (or subsequently Oset WTW) and the remaining 10% is supplied from Elvåga Lake (or subsequently Skullerud WTW).Hence, these values are set as the percentage split coefficient of water demand for the single subcatchment of the UWS from the two upstream service reservoirs in the 'Distribution Mains' table of the 'Operation' tab of the 'Water Supply Subsystem' form shown in Figure 5 7. Similarly, the available fixed cost of the total water distribution network is split up into two with this proportion. It is also assumed that the leakage percentage of both distribution mains is 22%. In addition, the annual rate of rehabilitation is assumed to be 1% of the total length for each distribution main. These data plus the energy required per unit volume of water conveyance which is equal in both distribution mains are specified in the 'Distribution Mains' table of the 'Asset' tab of the 'Water Supply Subsystem' form shown in Figure 5 9.

5.2.2. Subcatchment

The subcatchment in the UWS is represented here in an aggregated manner using a single WaterMet^2 Subcatchment with a single Local area. Note that modelling of multiple subcatchments can be highly beneficial especially for testing a variety of intervention options and allows the user to model the UWS with a high level of accuracy. Furthermore, in order to create more than one subcatchment, the required data would be the details of how the main pipelines are connected with each other and with service reservoirs, WTWs and water resources.

It is assumed that the single WaterMet^2 subcatchment contains the whole network of the pipelines of the distribution mains. This database comprising 28,442 pipes with lengths greater than 10 metres lists many pipe-characteristics (i.e. material type, length, diameter and age of pipes) in the UWS. A summary of this database is given in Table 5 1: and represented in Figure 5 10. These data are filled in the 'Distribution Network Pipelines' table of the 'Time Series' form shown Figure 5 11.

Table 5 1: A summary of pipelines' characteristics in the single subcatchment of the UWS

Material TYPE	TOTAL NUMBERS	TOTAL LENGTHS (KM)	DIAMETER RANGE (MM)	WEIGHTED AVERAGE DIAMETER (MM)	AGE RANGE (YEAR)	WEIGHTED AVERAGE AGE (YEARS)
Concrete	3	0.09	150	150	37	37
Ductile iron	11,680	462.1	50-1200	249	0-126	30
GRP	11	0.7	40-600	474	16-70	40
Grey cast iron	15,735	776.7	40-900	193	3-152	75
Mild steel	593	45.1	125-1600	582	15-141	61
PE	203	17.3	32-700	220	0-107	19
PVC	217	8.4	50-600	165	0-52	22
Total	**28,442**	**1,310,450**	**32-1600**	**226**	**0-152**	**58**

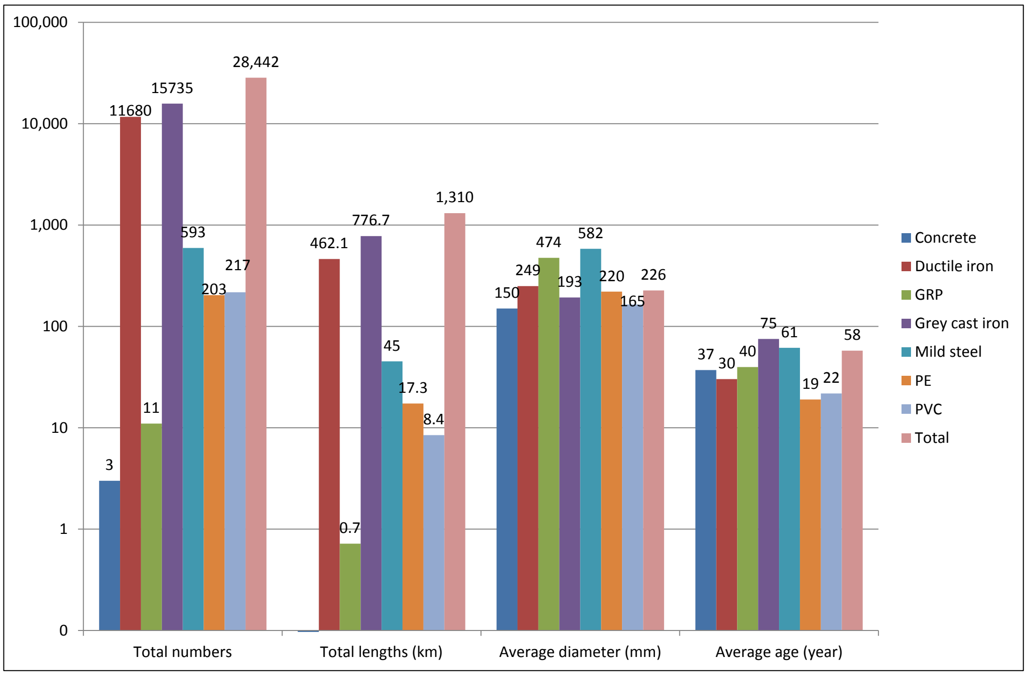


Figure 5 10: Summary of pipeline characteristics in the UWS

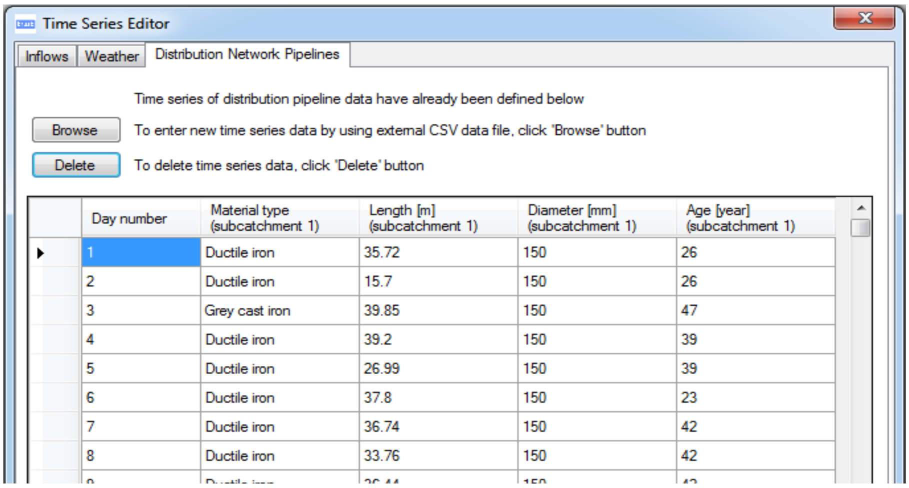


Figure 5 11: Filled 'Distribution Network Pipelines' table in the WaterMet^2 model

Figure 5 12 show the 'Topology' table of the single WaterMet^2 subcatchment in which the only single local area is linked to the only subcatchment. Also, this figure shows the two additional parameters for specifications of subcatchment (i.e. number of properties and total area) for the UWS. These parameters are related to water demand and rainfall-runoff modelling of the defined local area, respectively.

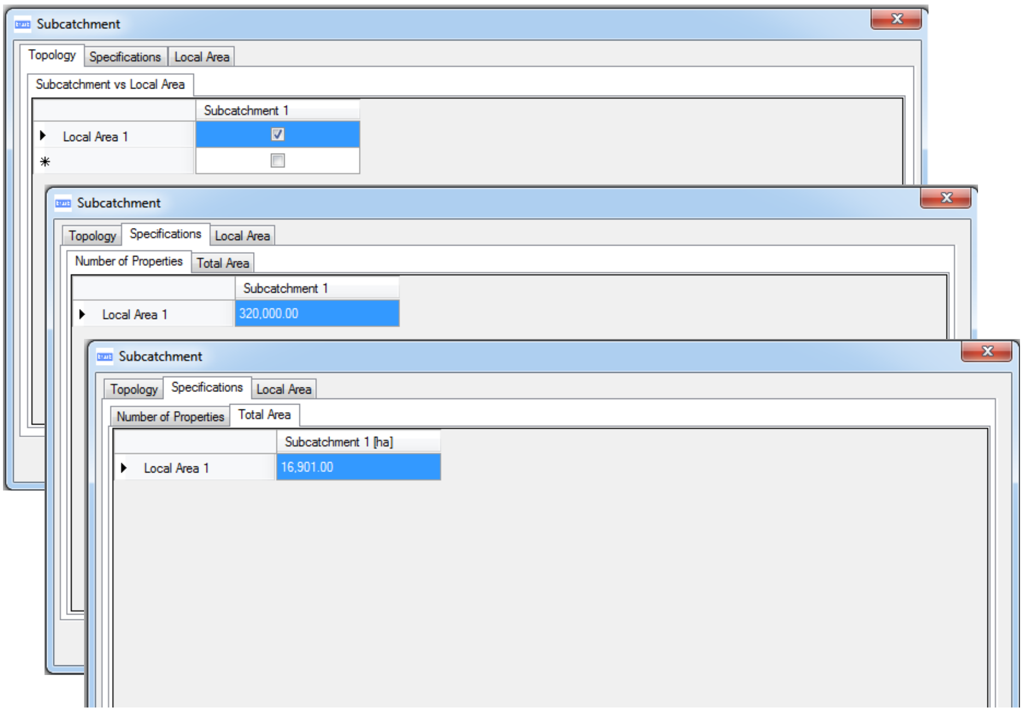


Figure 5 12: Filled 'Topology' and 'Specifications' tabs of the Subcatchment form for the WaterMet² model

Local area

The specifications of the defined local area including water demands and the parameters for rainfall-runoff modelling are populated in 'Local Area' table of 'Subcatchment' form shown in Figure 5 13. The data of the water demand is collected for the first year of analysis (i.e. 2011) from the available sources of the UWS (Oslo Water 2011a and b). Five types of water demand including indoor (e.g. domestic), industrial, irrigation, frost tapping and unregistered public use are specified in this figure. Further split of indoor water demand as the percentage of consumption for different appliances and fittings in the WaterMet² model is also filled out in the water demand 'Constants' table of 'Option' form shown in Figure 5 14.

Given the number of properties equal to 320,000, the average occupancy of each domestic property in the reference city in Figure 5 13 would be equal to 2.35 with respect to the population of 752,000 in 2011 for the urban area of the reference city. The total area of the pervious surfaces in the UWS constitutes the highest proportion (83.77%) of the total area with an infiltration rate of 0.3. The total area of all impervious surfaces (i.e. roof, pavement and road areas) in the UWS is slightly higher than 15%. Note that these surfaces can be potentially used for rainwater harvesting systems. Also, the average value of runoff percentage of for the impervious surfaces is assumed to be 95% for the local area.

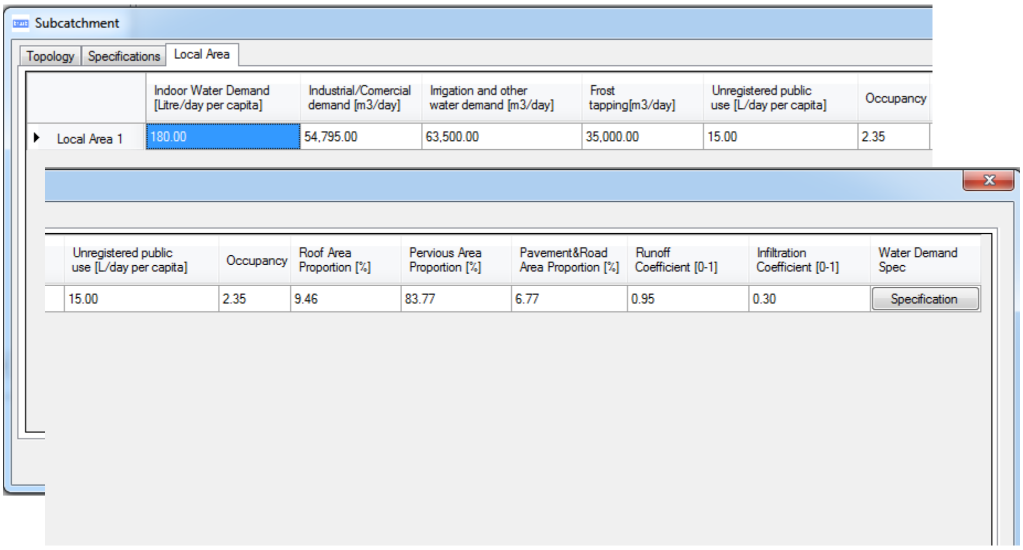


Figure 5 13: Filled 'Local Area' table of 'Subcatchment' form for the WaterMet^2 model

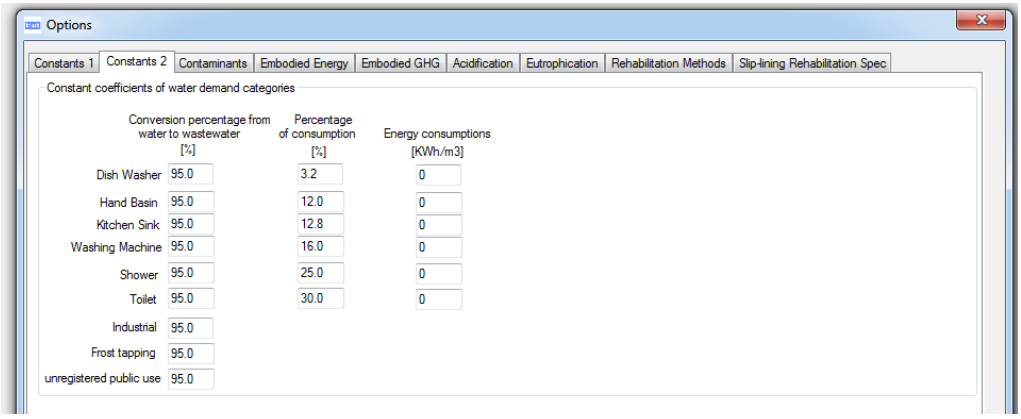


Figure 5 14: Filled water demand 'Constants' table of 'Option' form in the WaterMet^2 model

The variations of water demand for the UWS need to be specified in three temporal scales including annual, monthly and daily variations. The annual variations of water demand can be calculated based on a specific scenario for the projection of growth of population, industry and so on in the reference city. Hence, the annual increase of water demand for domestic, industrial and plant irrigation is assumed based on the fast growth of population over the planning horizon (Oslo Water 2011b) which is shown in Figure 5 15 and Table 5 2. It is assumed that frost tapping has no change over the planning horizon. These data are filled in the 'Annual Variation' table in 'Water Demand Specification' form shown in Figure 5 16.

Some water demand categories are defined for specific duration over a year. More specifically, plant irrigation for gardens and public open spaces is carried out for 108 days, the time interval from 15 May to 31 August. Also, water for frost tapping is required only for 151 days in the freezing time between 1 November and 31 March (Oslo Water 2011b). Other water demand categories exist over the entire year. Theses durations of water demand are set as start and end dates in the 'Daily Variations' tab of 'Water Demand Specifications' form shown in Figure 5 32. The monthly and daily variations of water demands can be adjusted based on the historic variation of water production in the UWS. Some water demand categories (e.g. irrigation water demand) are influenced by temperature variations. More details will be discussed in the model calibration section.

Table 5 2: Ratio of annual increase in water demands for different categories of users in the UWS between years 2010 and 2040

No.	WATER DEMAND CATEGORY	PERIOD 2010-2030	PERIOD 2030-2040
1	Domestic	1.02	1.01
2	Industry	1.02	1.01
3	Plant irrigation	1.02	1.01
4	Frost tapping	1	1
5	Unregistered public use	1.02	1.01

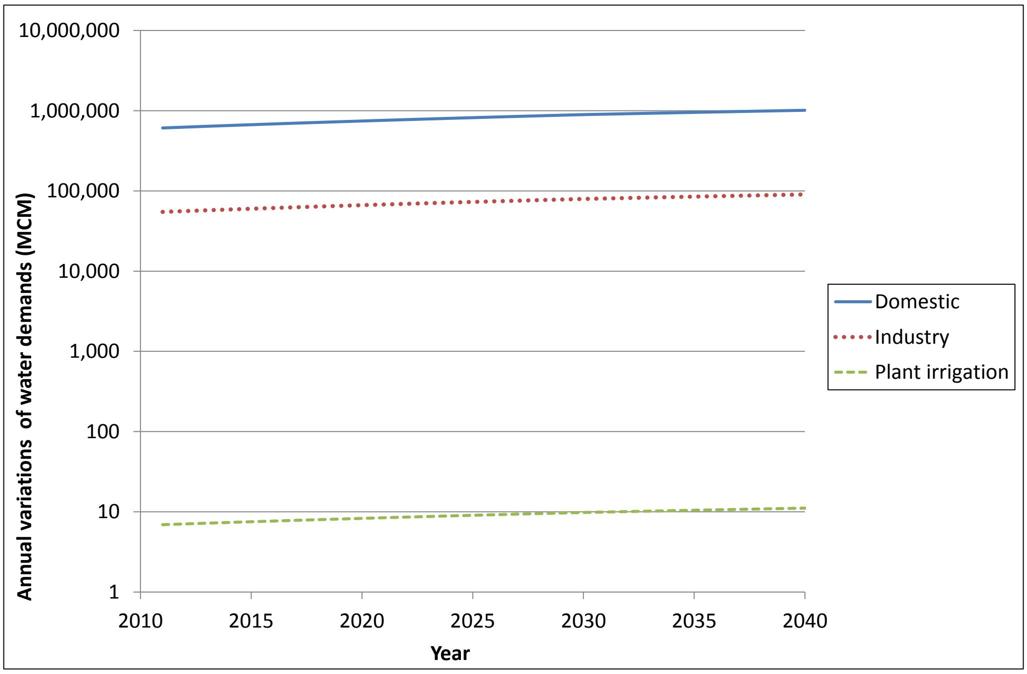
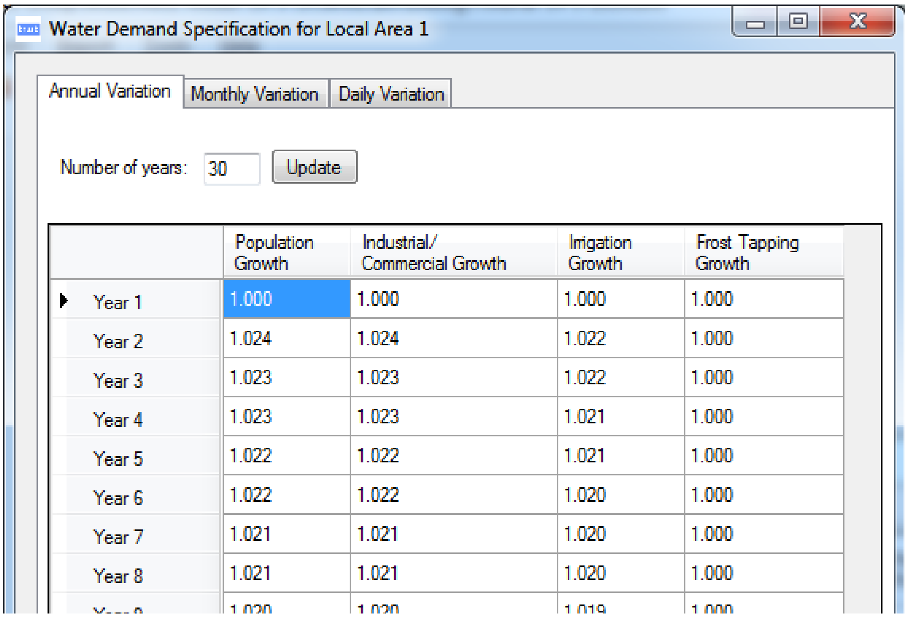


Figure 5 15: Annual variation in different types of water demand between years 2010 and 2040



	Population Growth	Industrial/ Commercial Growth	Irrigation Growth	Frost Tapping Growth
Year 1	1.000	1.000	1.000	1.000
Year 2	1.024	1.024	1.022	1.000
Year 3	1.023	1.023	1.022	1.000
Year 4	1.023	1.023	1.021	1.000
Year 5	1.022	1.022	1.021	1.000
Year 6	1.022	1.022	1.020	1.000
Year 7	1.021	1.021	1.020	1.000
Year 8	1.021	1.021	1.020	1.000

Figure 5 16: Filled 'Annual Variable' table of the 'Water Demand Specification' form in the WaterMet² model

5.2.3. Wastewater Subsystem

The existing sewer system of the reference city is a mix of combined and separate sewer systems: out of a total length of sewers, 37% is combined sewers, 30% sanitary sewers and 33% storm drains. Two WWTWs shown in Figure 5 1 collect 63% (WWTW1) and 37% (WWTW2) of the wastewater flow respectively (VAV, 2006). Two types of inflow discharging into the sewer system (i.e. sanitary sewage and runoff) are provided as follows: (1) the conversion coefficient for all types of water demand is assumed to be 95% which is filled in the table in ‘Option’ form shown in Figure 5 14; (2) daily time series of the weather data required for WaterMet^2 is extracted from Oslo Blindern station (eKlima2013). Consequently, climatology data of the reference city for the last 30 years (i.e. period 1981-2010) is assumed here for the calculation of runoff over the entire planning horizon. This time series is entered in the ‘Weather’ table in the ‘Time Series’ form shown in Figure 5 17. Note that the weather time series can be generated based on the synthetic data if appropriate.

As the wastewater subsystem in WaterMet^2 takes into account water quality modelling, the contaminants of interest and their concentrations based on the event mean concentration (EMC) for different types of water demand (sanitary sewage) and land surface (rainfall-runoff) need to be specified. For the purpose of this case study and considering the available data for the UWS, three contaminants including Total Carbon, Total Nitrogen and Total Phosphorus are defined and the relevant concentrations are filled in the ‘Contaminants’ table of the ‘Options’ form shown in Figure 5 18.

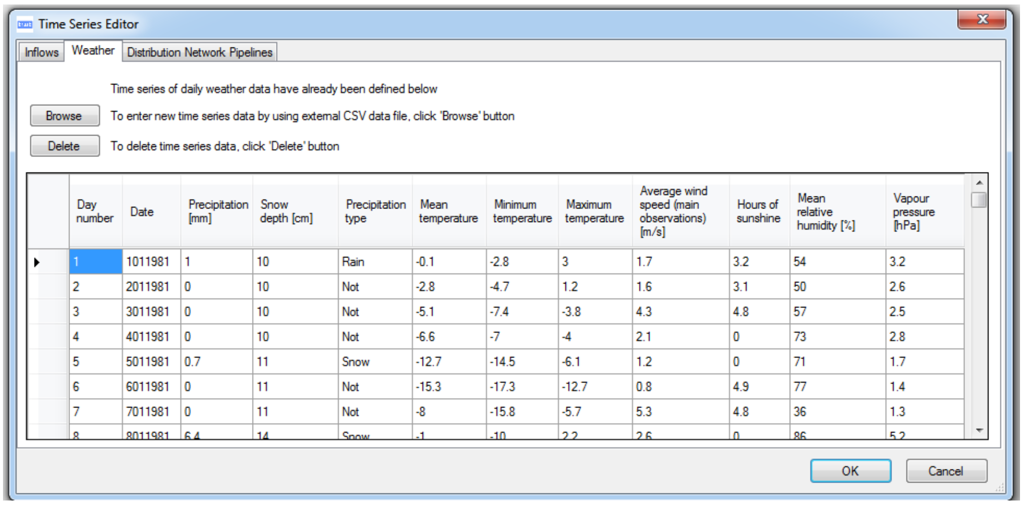
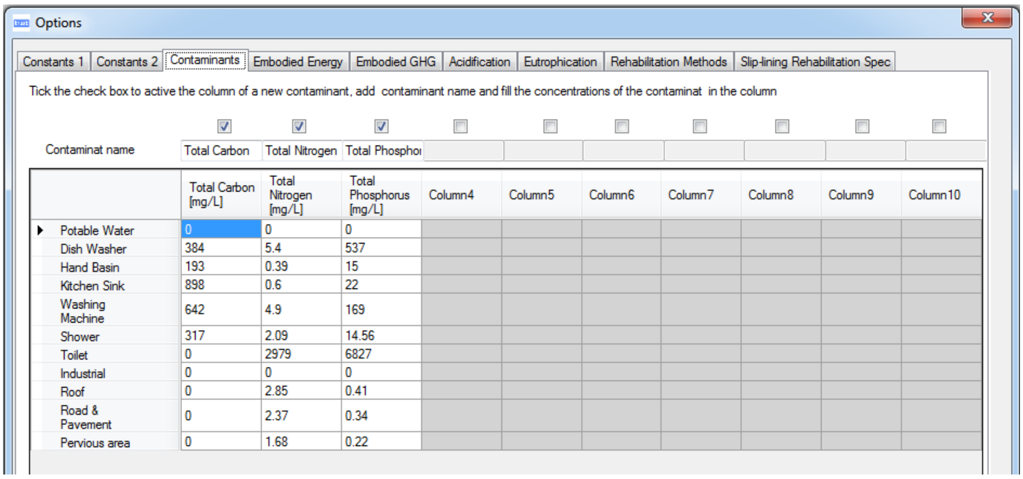


Figure 5 17: Filled ‘Weather’ table of the ‘Time Series’ form in the WaterMet^2 model



	Total Carbon [mg/L]	Total Nitrogen [mg/L]	Total Phosphorus [mg/L]	Column4	Column5	Column6	Column7	Column8	Column9	Column10
Potable Water	0	0	0							
Dish Washer	384	5.4	537							
Hand Basin	193	0.39	15							
Kitchen Sink	898	0.6	22							
Washing Machine	642	4.9	169							
Shower	317	2.09	14.56							
Toilet	0	2979	6827							
Industrial	0	0	0							
Roof	0	2.85	0.41							
Road & Pavement	0	2.37	0.34							
Pervious area	0	1.68	0.22							

Figure 5 18: Filled 'Contaminants' table of the 'Options' form in the WaterMet^2 model

Based on the UWS description outlined in section 5.1 and the layout in Figure 5 1, the topology of wastewater subsystem was constructed as displayed in Figure 5 19 and Figure 5 20. More specifically, the sewer system of the single subcatchment with no further downstream sewer system is considered as combined in Figure 5 19. The connection of this single sewer system to the two WWTWs is specified in Figure 5 20. Moreover, the overflow of both the single sewer system and the WWTWs is discharged into only one receiving water. This is specified in the 'Receiving Water' table of the 'Topology' tab shown in Figure 5 20.

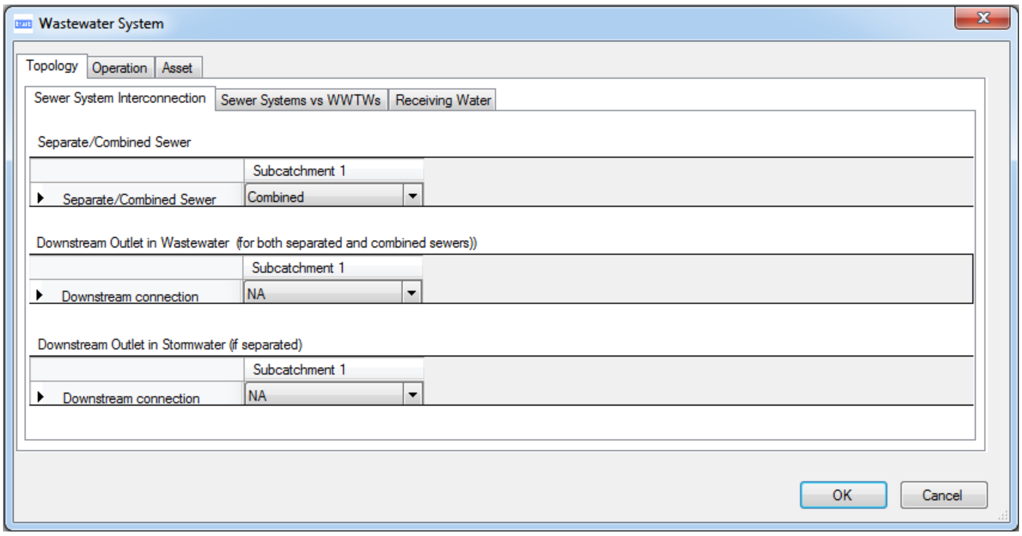


Figure 5 19: Filled 'Sewer System Interconnection' table under 'Topology' tab in the 'Wastewater Subsystem' form in the WaterMet² model

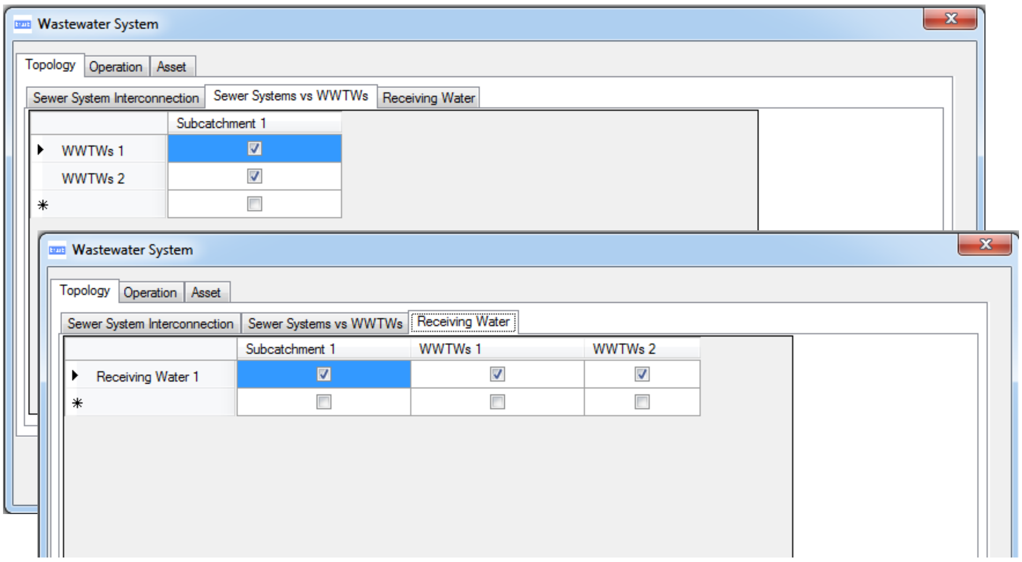


Figure 5 20: Filled 'component connection' tables under 'Topology' tab in the 'Wastewater Subsystem' form in the WaterMet² model

Figure 5 21 represents the filled 'Operation' tables of 'Wastewater' form for the WaterMet² model. As the collected wastewater and storm water are discharged into two downstream WWTWs. The percentage split coefficient from the sewer system of the single subcatchment to them needs to be specified. Based on the historic share of these two WWTWs, these percentage coefficients are considered as 37% and 63% for the two WWTWs. As the overflow of all three components is only discharged into one receiving water body, the split coefficient for each of them is obviously 100%.

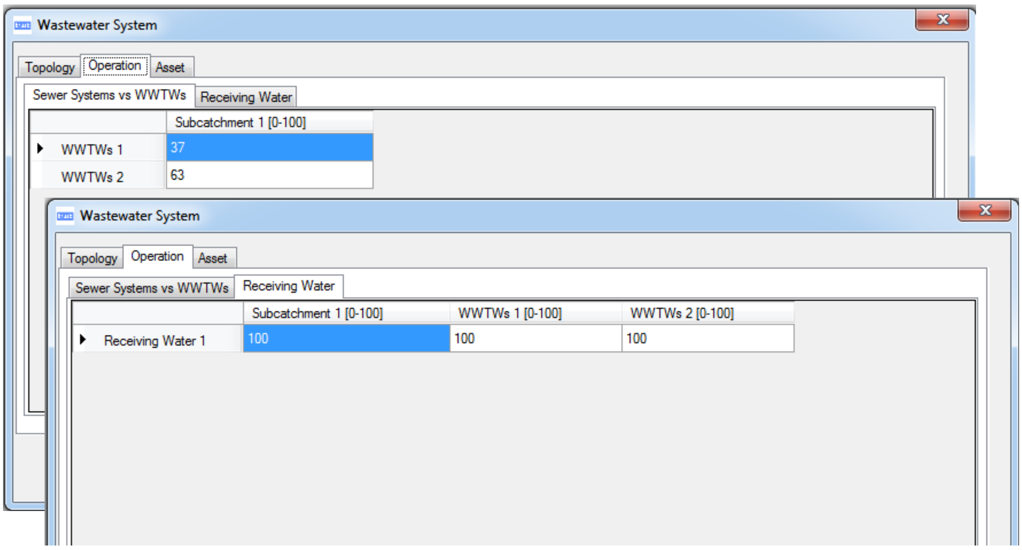


Figure 5 21: Filled 'Operation' tables in the 'Wastewater Subsystem' form in the WaterMet^2 model

Combined/Sanitary Sewer

The specifications of the sewer system related to the single subcatchment in the UWS are filled out in the 'Combined/Sanitary Sewer' table under 'Asset' tab in the 'wastewater subsystem' form shown in Figure 5 22. The water flow specifications (i.e. 'storage capacity type' and 'CSO capacity') are adjusted in the calibration process. More specifically, type of sewer system capacity (i.e. storage or transmission) plus CSO capacity are adjusted such that the simulated sewer system outflow conveyed to WWTWs match the measured inflow to the WWTWs. Infiltration and exfiltration coefficients are assumed to be zero for the sewer system although they can be considered in the calibration process. Other specifications (i.e. rehabilitation, energy and fixed operational cost) are filled out based on the annual report obtained from averaging the annual performance of the sewer system over the as the last decade (Venkatesh 2010).

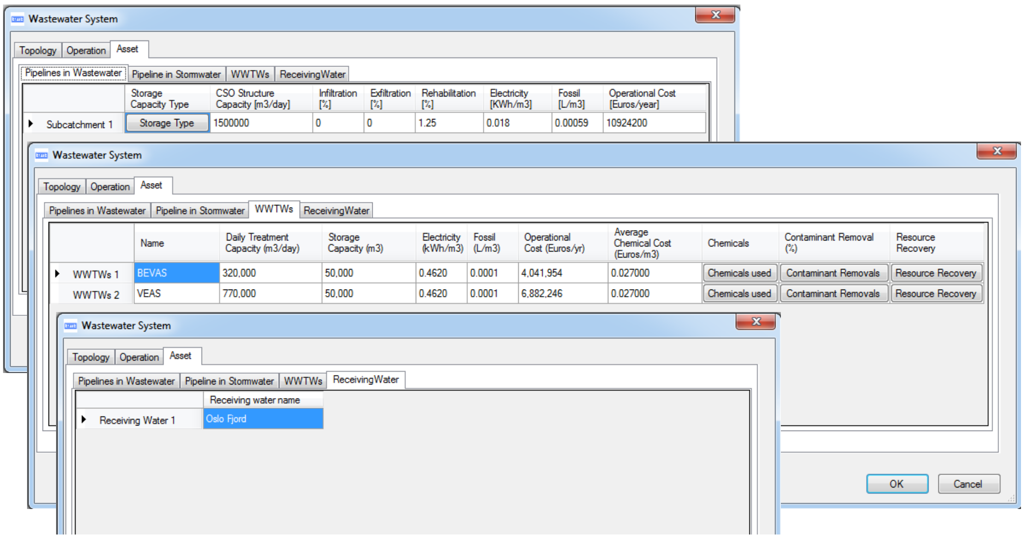


Figure 5 22: Filled 'Assets' tables in the 'Wastewater Subsystem' form in the WaterMet^2 model

WWTWs

The specifications of the two WWTWs are filled in the 'WWTWs' table under the 'Asset' tab of 'Wastewater Subsystem' form shown in Figure 5 22. The specifications of hydraulic capacities (i.e. daily treatment and storage capacities) are specified based on the existing conditions of the WWTWs but they can also be adjusted in the calibration process. Similar to the sewer system, other specifications (e.g. energy, operational costs and chemicals used) are specified based on the average of the annual performance reported from the WWTWs over the last decade (Venkatesh 2010). These values as well as the resources recovery are assumed to be identical for both WWTWs (Figure 5 23). Note that both WWTWs are generated all four types of the resource recovery (i.e. biogas, ammonium nitrate, single superphosphate and urea). However, the rate of the percentage removal for the three defined contaminants is different in each WWTW (Figure 5 24).

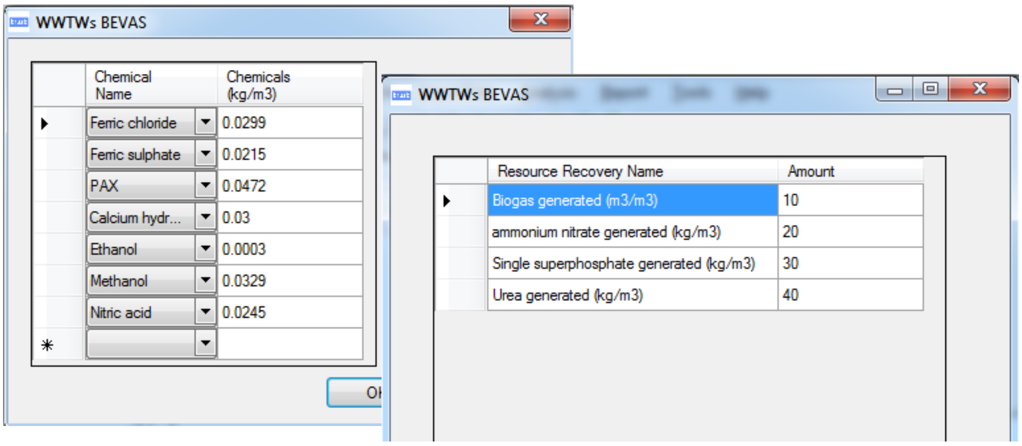


Figure 5 23: Specifications of chemicals used and resources generated in the WWTWs

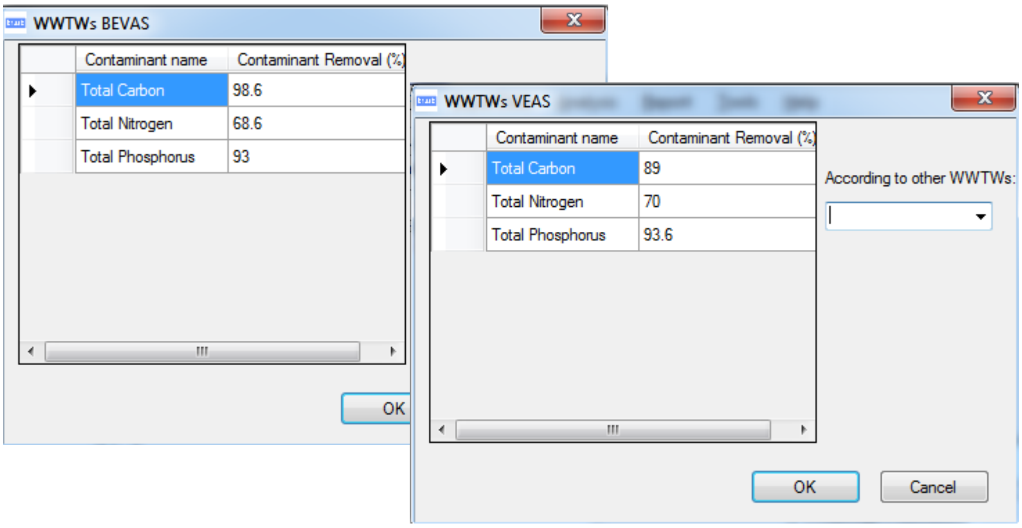


Figure 5 24: Specifications of contaminant removals in each of the WWTWs

5.2.4. Setting up other data

After setting the specifications of the UWS components, other data required for calculating the model performance indicator are specified in the 'Options' form shown in Figs. 5 26 till 5 31. More specifically, some general settings of the UWS specified in 'Constant 1' tab of the form shown in Figure 5 25 include climate constants, duration of planning horizon (30 years), and electricity and fossil fuel costs. Constant values of embodied energy, GHG emission, acidification and eutrophication used for the WaterMet^2 model are specified respectively in Figure 5 26, till Figure 5 29.

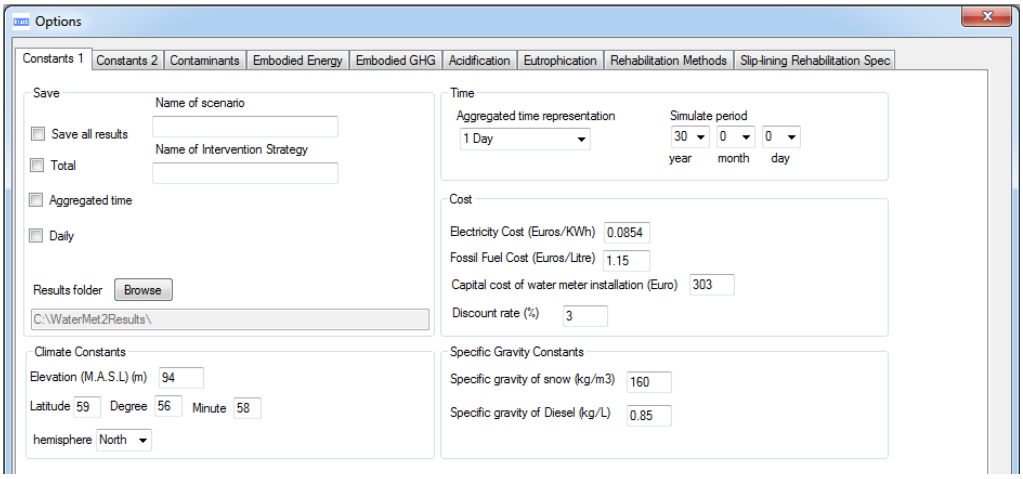


Figure 5 25: Filled 'Constant 1' tab in 'Options' form in the WaterMet^2 model

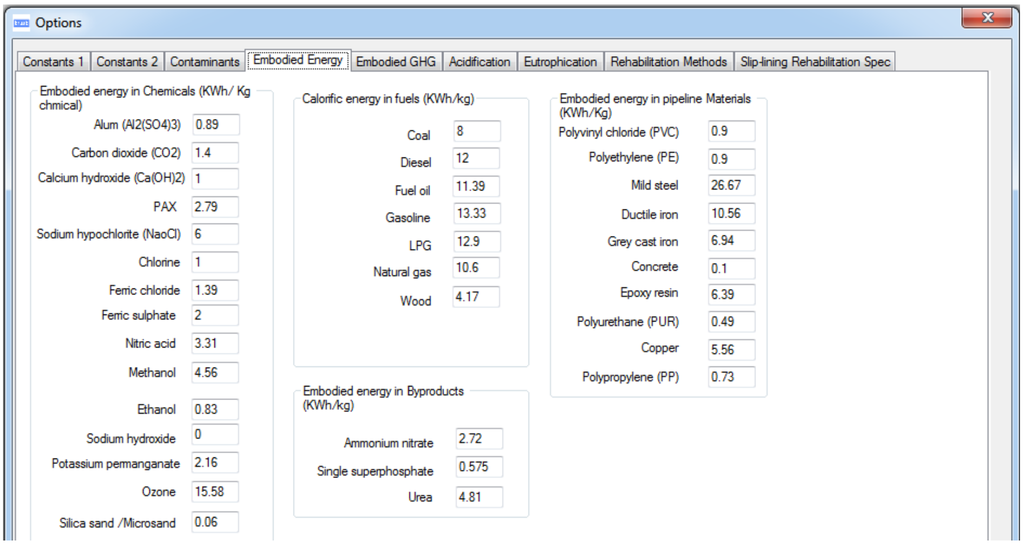


Figure 5 26: Filled 'Embodied Energy' tab in 'Options' form in the WaterMet^2 model

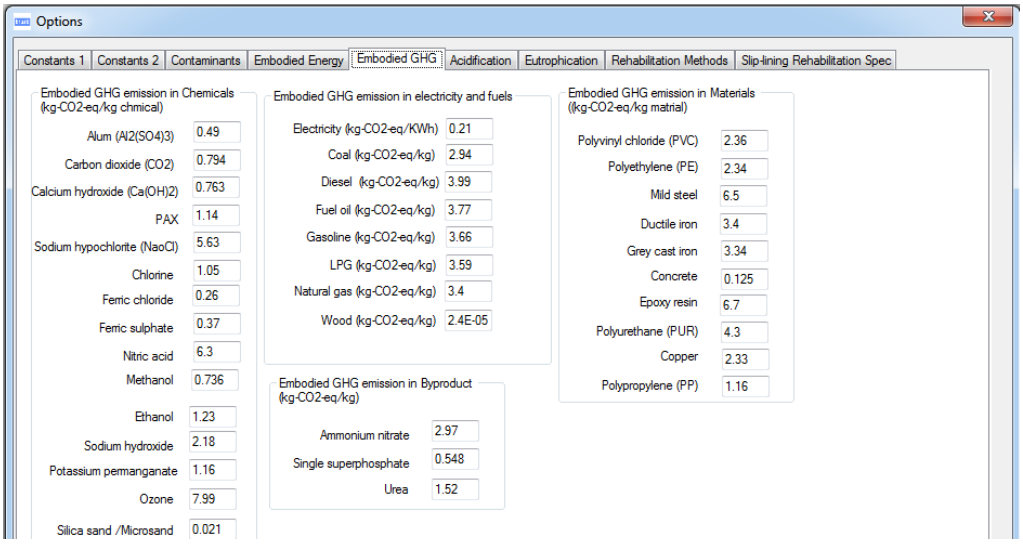


Figure 5 27: Filled 'Embodied GHG' tab in 'Options' form in the WaterMet^2 model

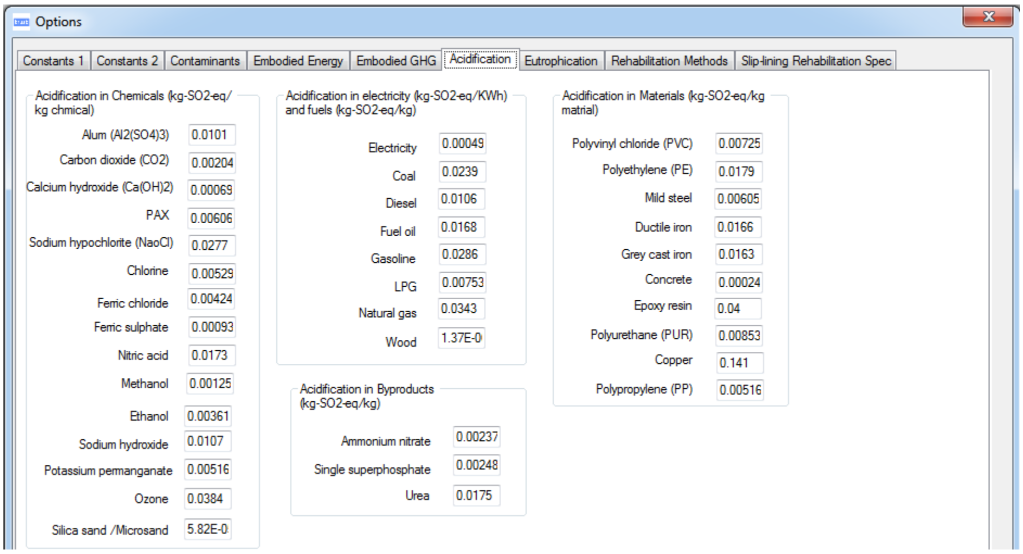


Figure 5 28: Filled 'Acidification' tab in 'Options' form in the WaterMet^2 model

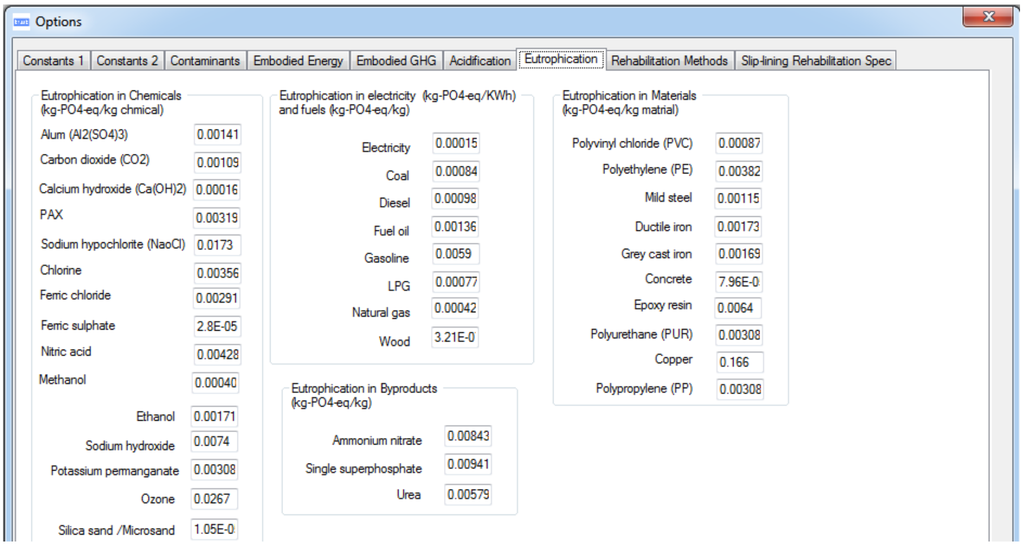


Figure 5 29: Filled 'Eutrophication' tab in 'Options' form in the WaterMet^2 model

The specifications of four types of the rehabilitation conducted in the water distribution network are filled in the last two tabs (i.e. 'Rehabilitation Methods' and 'Slip-lining Rehabilitation Spec') of the 'Options' form shown in Figure 5 30. The cost and GHG emissions associated with the benchmark method (i.e. Slip-lining with PE pipe) are specified in the last tab and the characteristics of other methods are specified as a coefficient of the benchmark. The highest portion of Oslo pipeline rehabilitation is related to 'Lining with PU' method with 40% of the entire rehabilitation works but its cost and GHG emissions are half of the benchmark. Other three methods including the benchmark have equal share (20%) in Oslo rehabilitation but the costs and GHG emissions associated with them are different. More specifically, 'Rebuilding with ductile iron pipe' method is 5 times more expensive and 10 times more GHG is emitted compared to the benchmark method but both cost and GHG emissions of the 'Pipe cracking + lining' method is 50% more than the benchmark method.

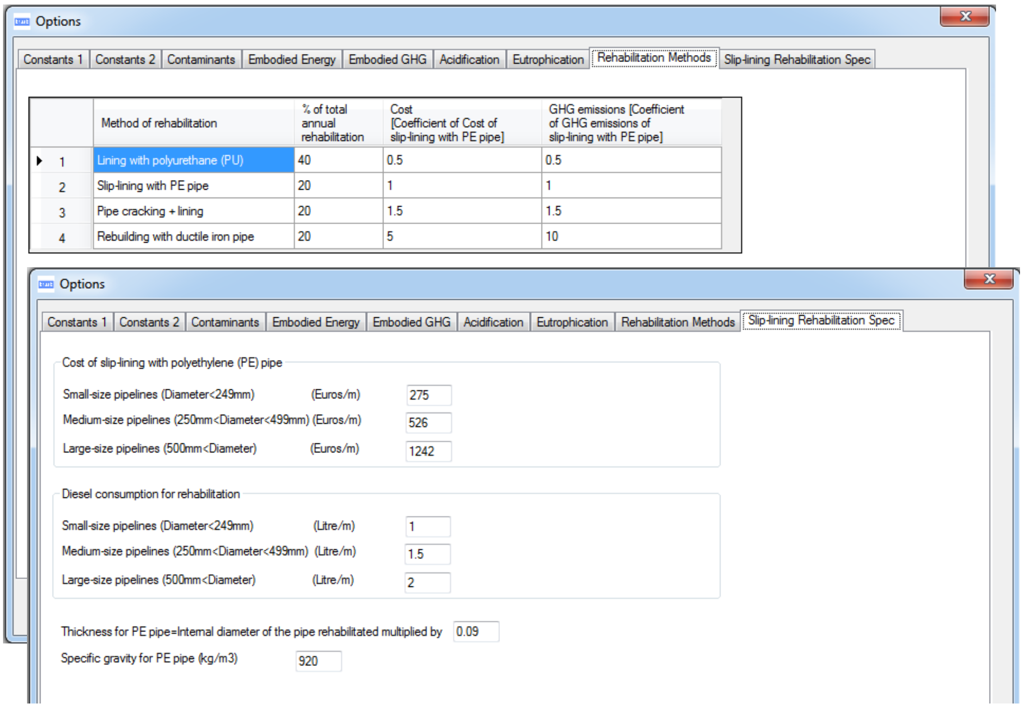
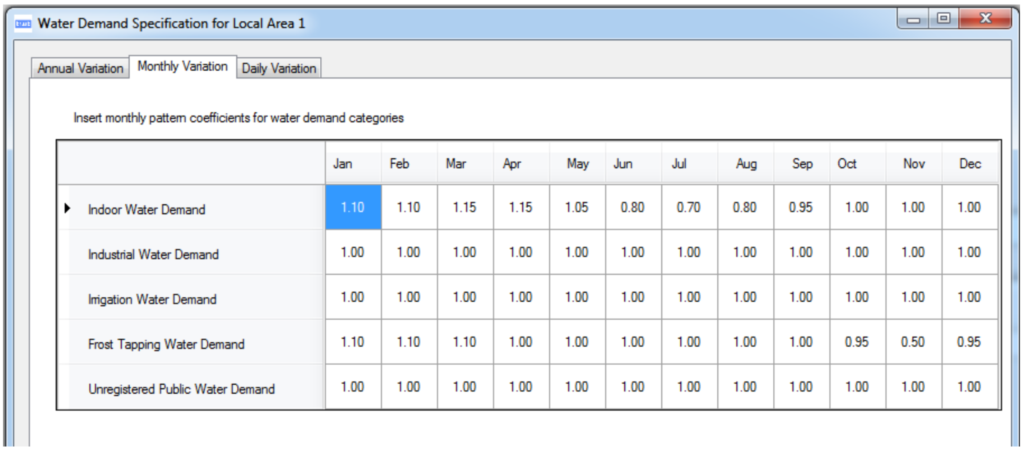


Figure 5 30: Filled 'Rehabilitation Methods' and 'Slip-lining Rehabilitation Sepc' tabs in 'Options' form in the WaterMet^2 model

5.3. The WaterMet^2 Model Calibration

The WaterMet^2 model as a conceptually based model can be calibrated with data from either historic measurements or the result of physically based models. The calibration of the WaterMet^2 model is conducted with the historical daily measurements of potable water provided in WTWs and wastewater entered in WWTWs.

The water supply subsystem in the WaterMet^2 model is first calibrated for two years of recorded daily water production at WTWs split into two periods using 2011for calibration and 2012 for validation. The calibration parameters which are adjusted in the potable water supply subsystem model include (1) monthly coefficients of water demand profiles (Figure 5 31); (2) percentage contribution of daily temperature in daily variation of water demand profiles (Figure 5 32). The adjusted coefficients shown in these figures are applied for the entire years of the planning horizon. As shown in Figure 5 32, the water demand variations for industrial water demand assumed to be independent from temperature while the other water demand profile are fully influenced proportional to temperature variation. The variations which cannot be correlated with temperature can be adjusted by monthly variations. For instance as it can be seen in Figure 5 31, indoor water demands highly fluctuates especially during the late spring and the entire summer not because of temperature but as a result of some activities such as tourism or vacation. Considering the average air temperature, the coefficients of both daily and monthly variations of all water demand categories are shown in Figure 5 33.


Water Demand Specification for Local Area 1

Annual Variation | Monthly Variation | Daily Variation

Insert monthly pattern coefficients for water demand categories

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Indoor Water Demand	1.10	1.10	1.15	1.15	1.05	0.80	0.70	0.80	0.95	1.00	1.00	1.00
Industrial Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Irrigation Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Frost Tapping Water Demand	1.10	1.10	1.10	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.50	0.95
Unregistered Public Water Demand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 5 31: Filled 'Monthly Variable' table of the 'Water Demand Specification' form in the WaterMet^2 model

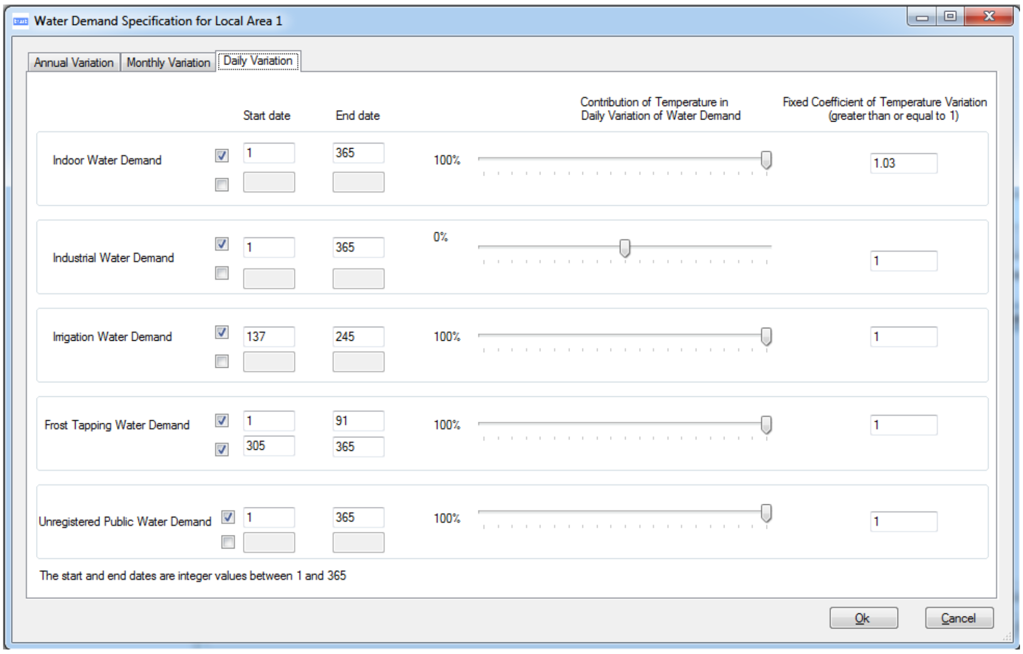


Figure 5 32: Filled 'Daily Variable' table of the 'Water Demand Specification' form in the WaterMet^2 model

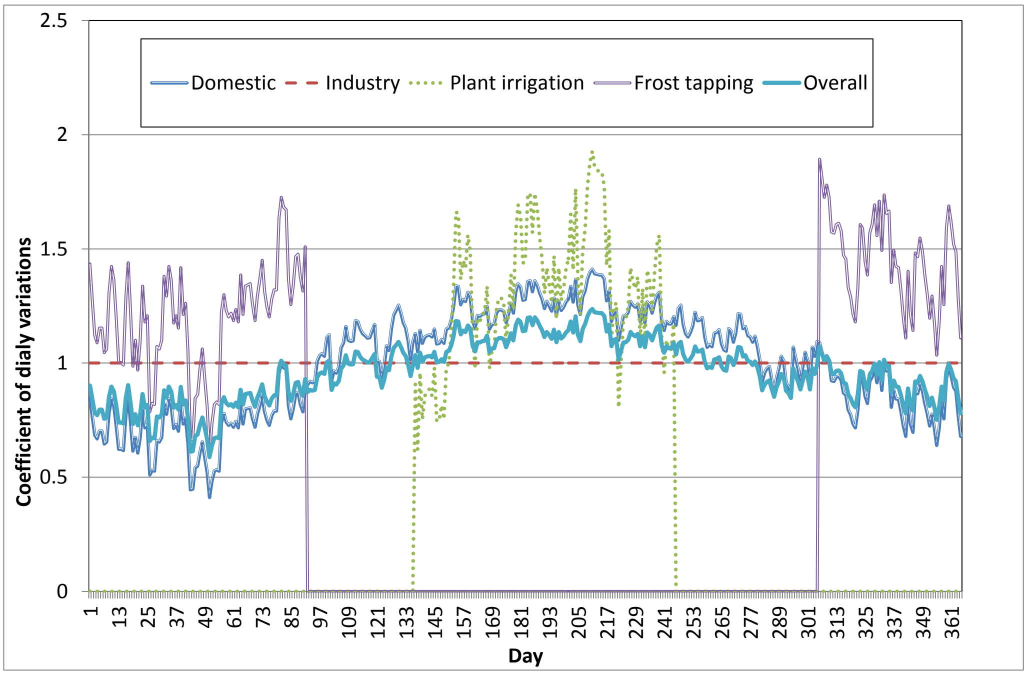


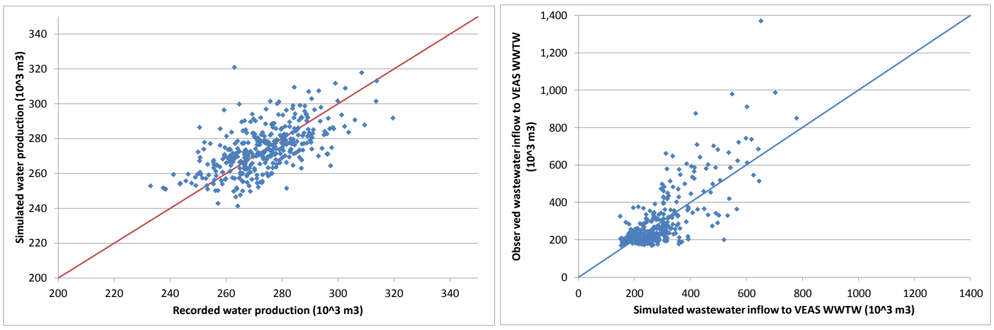
Figure 5 33: Coefficients of daily variations for different categories of water demand

The wastewater subsystem model is subsequently calibrated for two years (2010-2011) of recorded daily wastewater inflows to the main WWTW (i.e. VEAS), again split into two one-year periods for calibration and validation. The relevant calibration parameters are hydrologic parameters of the local area and the principal hydraulic features of the WWTWs and sewer system. More specifically, these parameters are runoff and infiltration coefficients in the local area (Figure 5 13) and storage capacity coefficients of sewer system and its CSO storage capacity plus daily treatment and storage capacities of WWTWs in wastewater subsystem (Figure 5 22). Figure 5 34 shows a graphical comparison of the model performance for the validation period in both subsystems (i.e. water supply and wastewater) plotting the simulated versus observed values on *x-y* plot. Although both graphs show a fair amount of scatter about the 1:1 line, the simulated results in both parts of the integrated model are reasonably close to the observed values. In addition, Figure 5 35 and Figure 5 36 show the performance of the wastewater model based on a comparison between observed and simulated values on a hydrograph during the calibration and verification periods, respectively. As can be seen, the simulated values closely track the observed values for both periods in the hydrographs.

Further evaluation of the model performance is undertaken by measuring three quantitative statistics recommended by Moriasi *et al.* (2007): (1) *the Nash-Sutcliffe efficiency (NSE)*: indicating how well the plot of observed versus simulated data fit the 1:1 line with an optimal value of 1.0 and an acceptable range between 0.0 and 1.0 (Nash and Sutcliffe, 1970); (2) *RMSE-observations standard deviation ratio (RSR)*:as the ratio of the root mean square error (RMSE) and standard deviation of the measured data and thus the optimal value is 0.0; (3) *Percent bias (PBIAS)*:as the average tendency of the simulated data to be larger or smaller than their observed counterparts. Table 5 3 gives a summary of the performance for both subsystems in the calibration and validation periods with respect to these statistics. As can be seen, the accuracy of the model of the water supply subsystem is not as good as that of the wastewater subsystem. This can be attributed to the fact that daily water demands are highly variable and stochastic over a year, not necessarily corresponding with temperature and monthly variation; and thus cannot be captured by the WaterMet^2 model. Such an accuracy for the model calibration of the water demand has also been reported in the previous conceptual models such as *Aquacycle* (Mitchell *et al.,* 2001) and CWB (Mackay and Last, 2010). However, the model accuracy can be improved either through increasing the extent of the measured data for the basis of the calibration and/or through automated (e.g. optimised) calibration. The statistics of the simulated performance for the wastewater subsystem indicates a better accuracy of modelling 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).

Table 5 3: Simulation performance of the WaterMet^2 model

	WATER SUPPLY SUBSYSTEM		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



(a) (b)

Figure 5 34: Daily simulated result in WaterMet^2 versus recorded values for validation period in (a) water production (b) wastewater inflow to VEAS WWTW

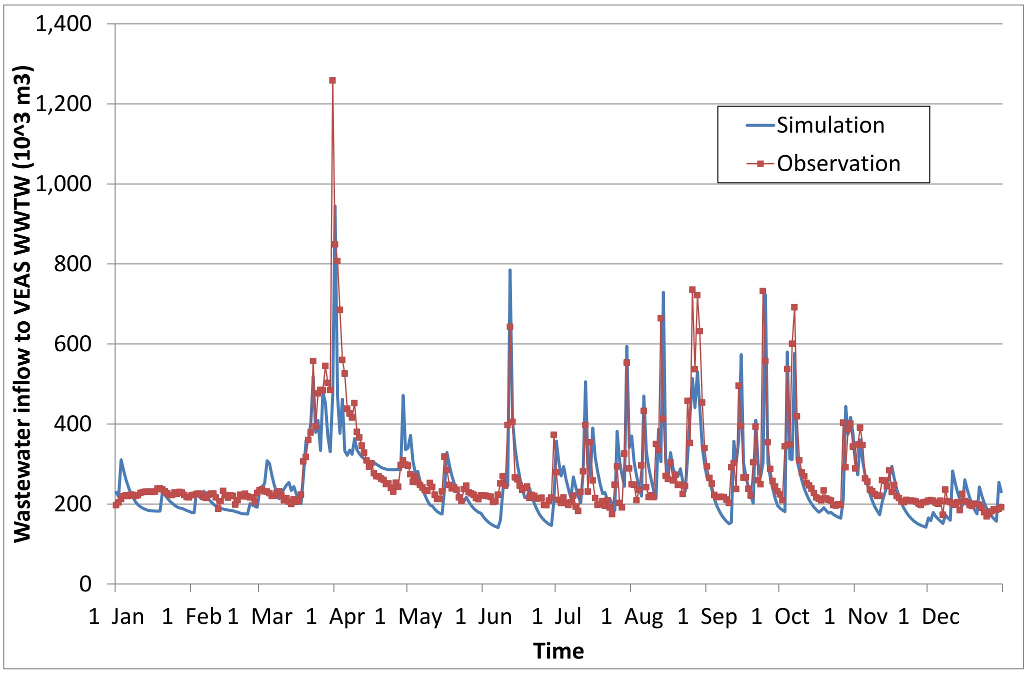


Figure 5 35: Daily simulated versus recorded wastewater inflow to VEAS WWTW for the periods of calibration (2010)

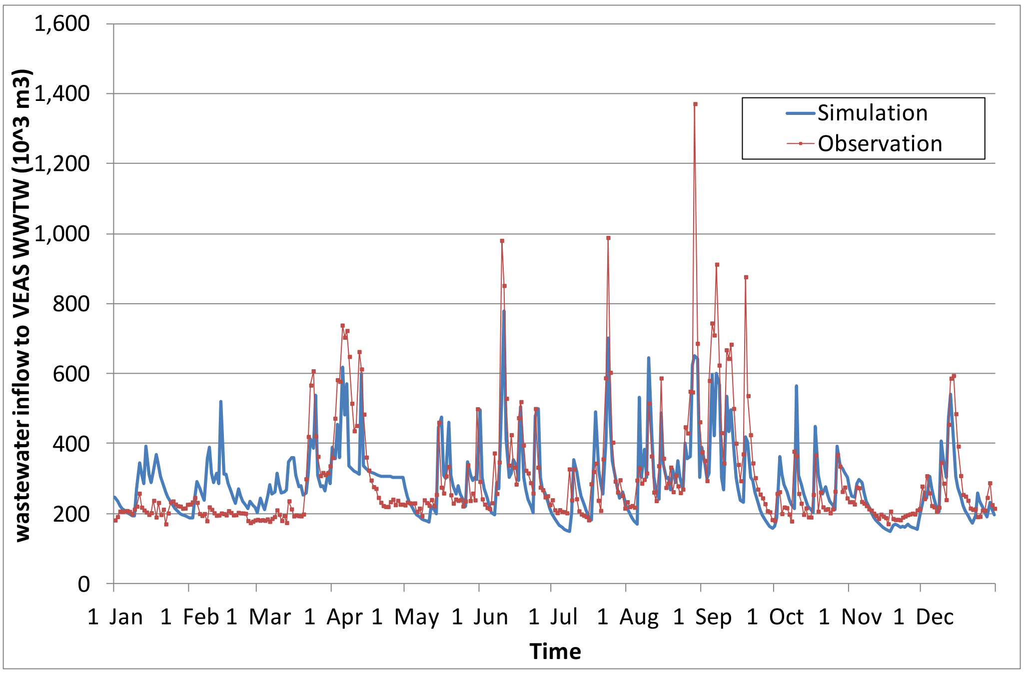


Figure 5 36: Daily simulated versus recorded wastewater inflow to VEAS WWTW for the periods of validation (2011)

5.4. Quantification of the Existing UWS Performance

Once the model is calibrated, the result of the UWS WaterMet^2 model can be viewed in terms of different quantitative KPIs. These quantitative KPIs can be used as metrics for some specific criteria especially when comparing different scenarios or introducing different intervention options in the model. When running the WaterMet^2 model, the quantitative KPIs can be obtained in two ways: (1) those which are directly supported by the WaterMet^2 model and are available in list of KPIs of the software tool; (2) those which are not available in that list but their calculation is supported by the KPIs in the list. In this section, some instance of the KPIs for each component as well as the entire UWS are presented and analysed for the entire planning horizon with daily time step. The definitions and relations used to calculate these KPIs were described in the previous chapter.

One of the KPIs in water supply flow is the percentage of water demand delivered. This KPI is available in the list of KPIs in the software tool. Figure 5 37 indicates the time series of this KPI for the WaterMet^2 model over the period 2011-2040. As shown in this figure, the water shortage kicks in after a few years of starting the planning horizon shortly and infrequently probably depending on climate and the inflows in water resources. However, it gradually tends to worsen, particularly in summer in the last years of the planning horizon when the water shortage expands to the whole year (see the percentage of finishing years in the figure for which there is no 100%water supply at any time). This figure shows that proceeding with the existing configuration in the UWS would even lead to a critically challenging water supply during the last years of planning horizon such that the water demand delivered will reach up to around 60%.

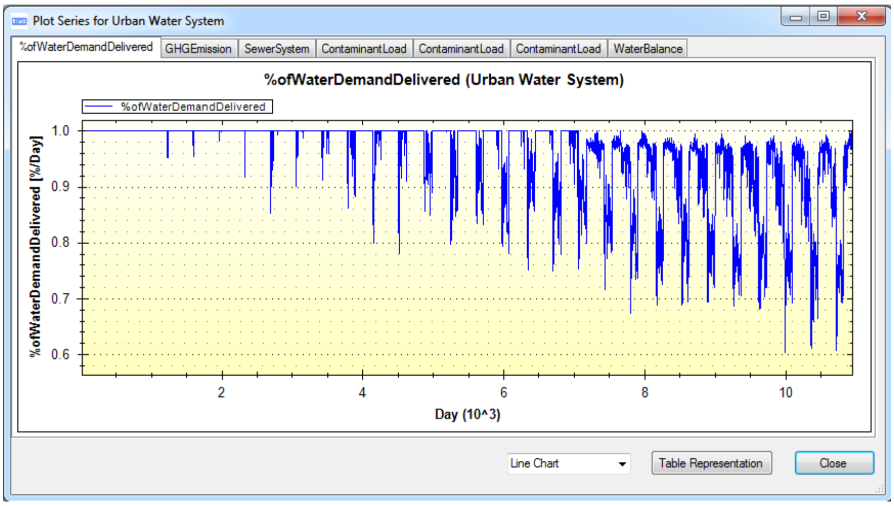


Figure 5 37:% of water demand delivered in the UWS

Figure 5 38 illustrates the annual ratio of water demand delivered in the WaterMet^2 model. Further, this ratio can be represented in WaterMet^2 with other aggregated times. Thus, water supply reliability can be obtained through this KPI if aggregated time is set to the 'simulation period'. As a result, the reliability of water supply is obtained from the ratio of the total water delivered to the total water demand in the UWS.

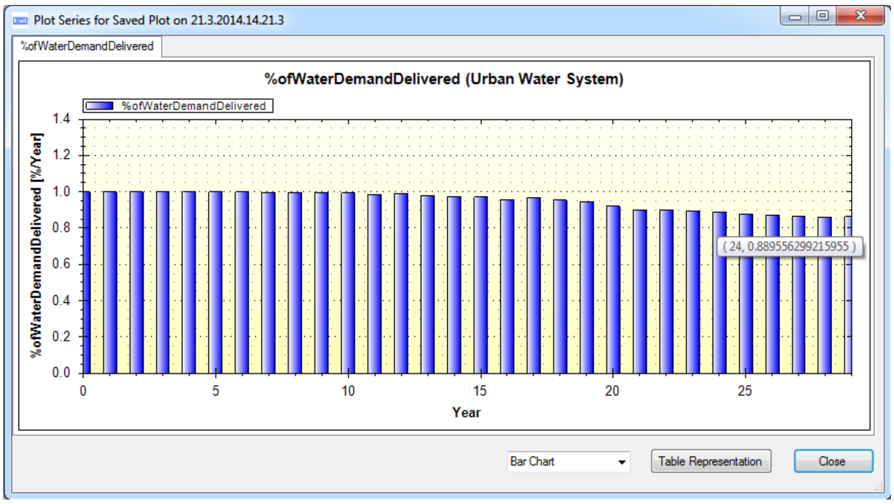


Figure 5 38: Annual percentage of water demand delivered in the UWS

The KPIs related to water flow (i.e. total water demand, total water delivered and total leakage) in the model are tracked down in WaterMet^2 as shown in Figure 5 39. As seen in this figure, the water delivered is confined to some specific limit which is unable to fully supply the demand especially in the last decade of the planning horizon. Also, total water leakage is calculated based on the leakage volume in the water distribution network with respect to the degree of pipeline rehabilitation during the planning horizon. Unlike the increasing trend of water demand, the leakage rate follows almost a stationary trend as it is assumed to be proportional to water delivered.

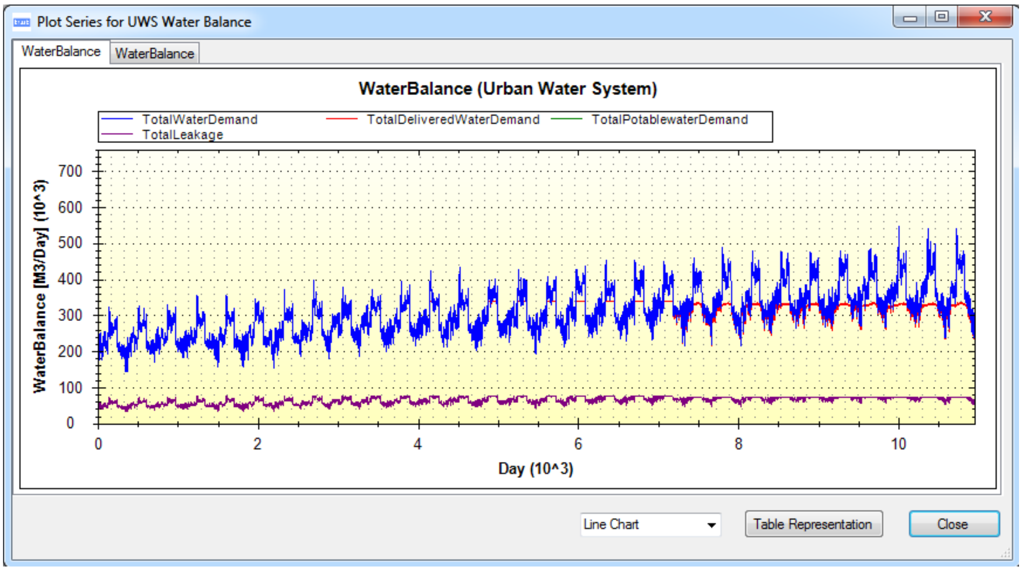


Figure 5 39: Main metrics of potable water balance in the water supply subsystem

The consumed energy in the reference city originates from three sources including fossil fuel, electricity (direct) energy and embodied (indirect) energy resulted from pipeline rehabilitation and chemicals used for the treatment. Accordingly, the GHG emissions are calculated in kg-CO_2 equivalent as a result of consumption of different sources of energy. Figure 5 40 and Figure 5 41 depict the time series of energy consumed and GHG emissions over the planning horizon in the UWS, respectively. As shown in Figure 5 40, the highest proportion is for electricity energy while the fossil fuel contributes a small proportion of the total energy. Unlike the time series of energy, embodied GHG emissions has the highest proportion of total GHG emissions. This discrepancy in the proportion can be attributed to significant contribution of the GHG emissions of the chemicals, which are far more than that of electricity. In addition, the high oscillation of the embodied GHG emissions can be linked to the highly changing storm water runoff entered the WWTWs which cause chemicals used for treatment change with high variations. Similarly, the time series of acidification and eutrophication can be tracked down as the available KPIs in the WaterMet^2 model.

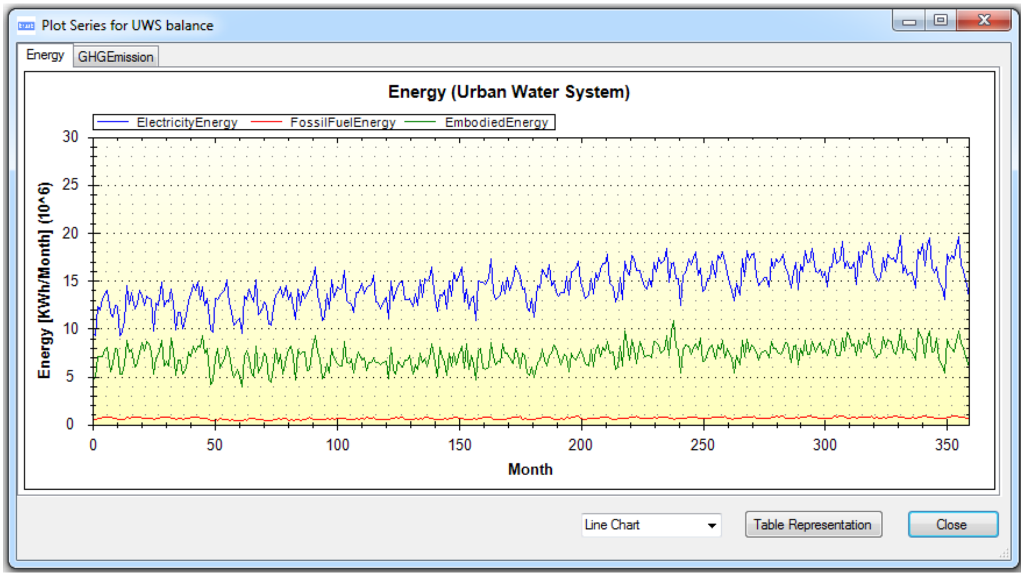


Figure 5 40: Fluctuation of different types of energy usage in the UWS over the planning horizon

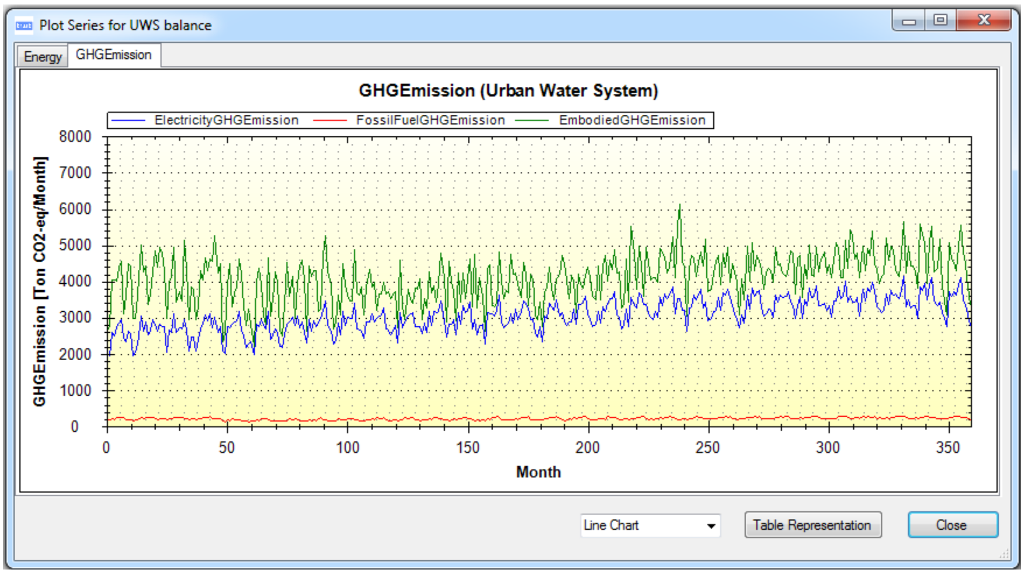


Figure 5 41: Fluctuation of GHG emitted from different sources in the UWS

One of the KPIs which can be calculated for each component as well as the entire UWS is costs dividing into two parts of capital and operational costs. Figure 5 42 shows the times series of these costs for the UWS model. The operational cost covers both fixed and variable (water consumption-dependant) costs for all components. The oscillations of the operational cost in the UWS model are relatively small with a smoothly increasing trend over the entire planning horizon as there are no significant changes in the UWS operation except the consistent water demand growth.

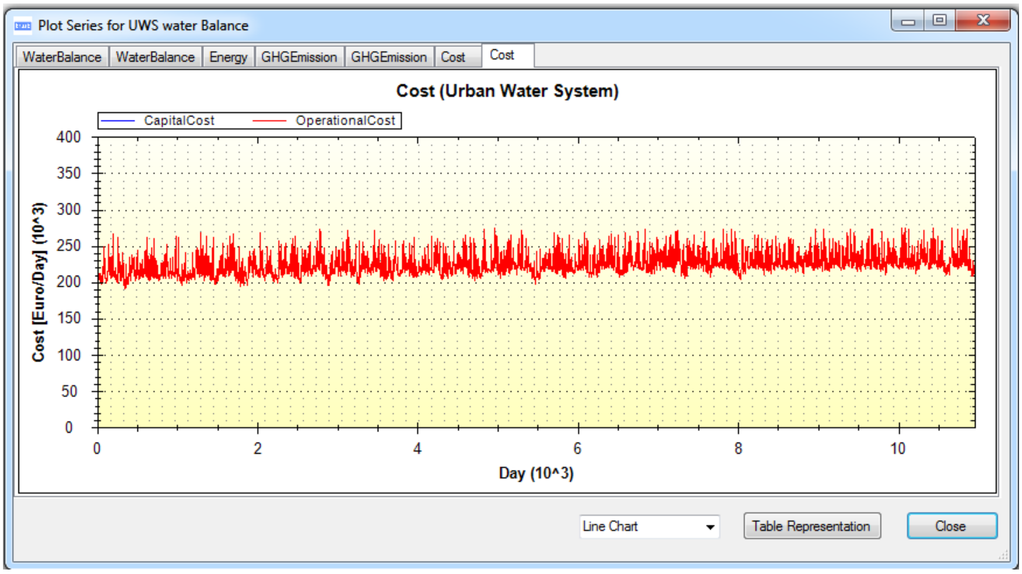


Figure 5 42: Capital and operational costs in the UWS

The user can track down the water flows in the storage components of The WaterMet[2] (e.g. water resources and service reservoirs). For instance, Figure 5 43 and Figure 5 44 represent the different water flows in the two water resources in the UWS model. Furthermore, the variations of the volume in the two service reservoirs are shown in Figure 5 45 and Figure 5 46. As it can be seen, the water inflows into the main service reservoir (i.e. Maridalsvannet Lake) are often far more than the water demand over the planning horizon. Consequently, overflow frequently occurs in this water resource with respect to its capacity (see Figure 5 45).

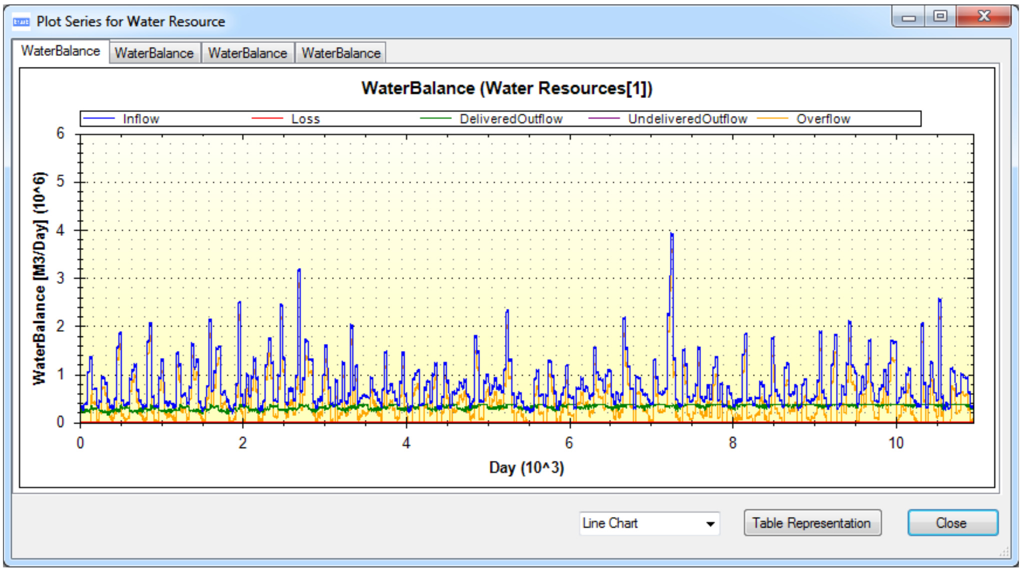


Figure 5 43: Different water flows in Maridalsvannet Lake

On the other hand, the second water resource has no enough storage capacity compared to the water withdrawal. As can be seen in Figure 5 46, the storage is filled over the first years and even there is some overflows once the water resource becomes full (see Figure 5 44). As soon as the increasing water demand overtakes the water inflow, the storage begins discharging steadily (see Figure 5 46). Finally undelivered outflow happens when there is no storage in the resource and water demand is greater than water inflow as shown in Figure 5 44. One of the remedy which can be proposed for this water shortage is to change the percentage split coefficient of water allocation from the other water resource which typically has additional water available. However, this needs to be rigorously analysed as the capacity of other components can influence as a limiting factor.

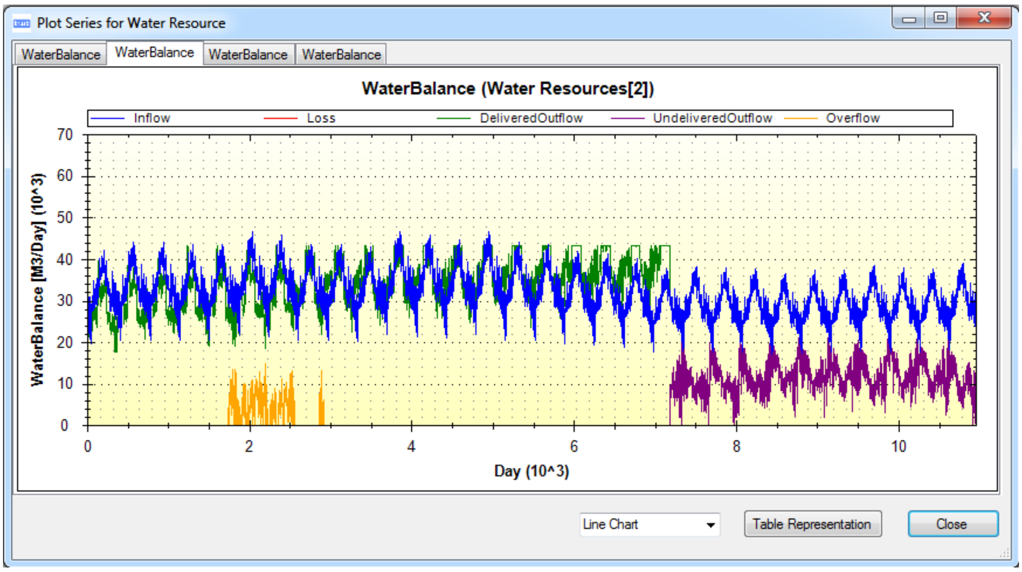


Figure 5 44: Different water flows in Elvåga Lake

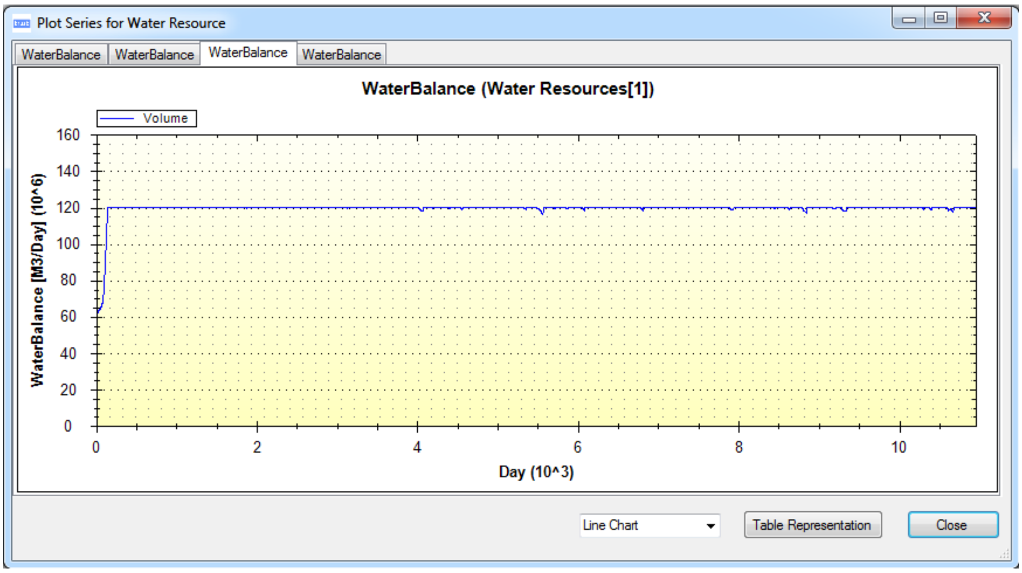


Figure 5 45: Volume of Maridalsvannet Lake over the planning horizon

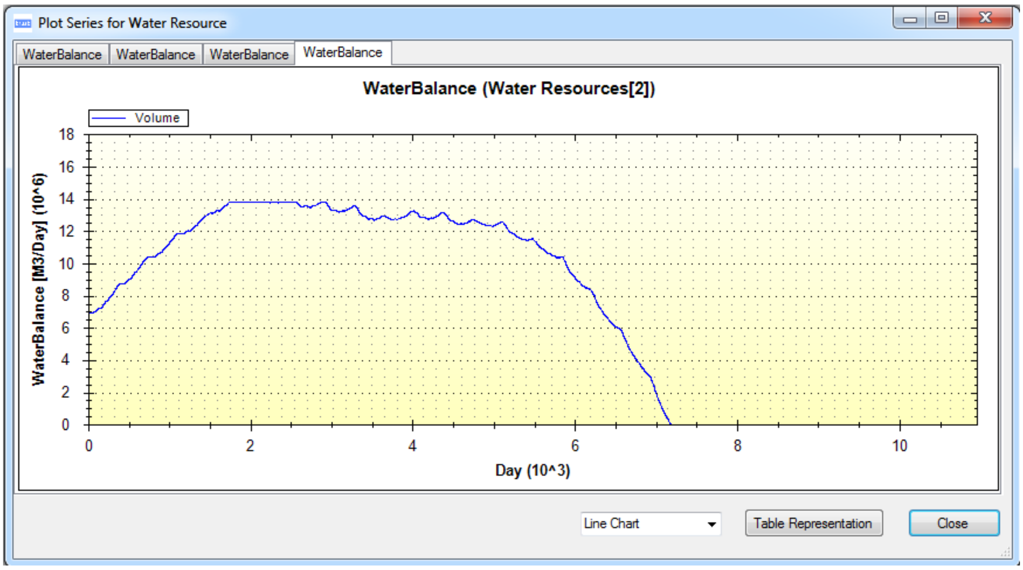


Figure 5 46: Volume of Elvåga Lake over the planning horizon

Figure 5 47 and Figure 5 48 shows the water flows of the two WTWs in the WaterMet^2 mode. As can be seen, the undelivered outflow in the main WTW (i.e. Oset) happens when the water demand increases as much as the WTW treatment capacity (i.e. 370,000 m^3/day). As the upstream water resource for this WTW can provide enough raw water, there is no lack of inflow to the WTW. However, undelivered outflow for the small WTW (i.e. Skullerud) occurs due to both reasons of lack of inflow and exceeding capacity. The latter was discussed in the above but the former happens in the middle of the planning horizon when the water demand exceeds the WTW capacity (i.e. 43,200 m^3/day). Note that, the undelivered outflow in both WTWs follows a cyclic behaviour which experiences its peak during summer and diminishes during winter. In both figures, water inflow superimpose delivered outflow and there is no overflow happening during the planning horizon.

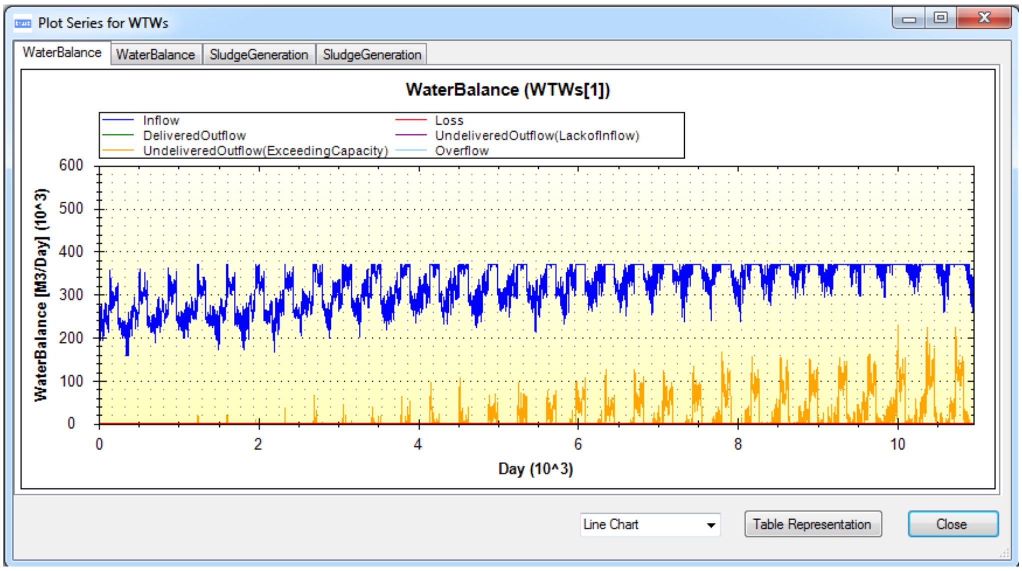


Figure 5 47: Fluctuations of different water flows in Oset WTW

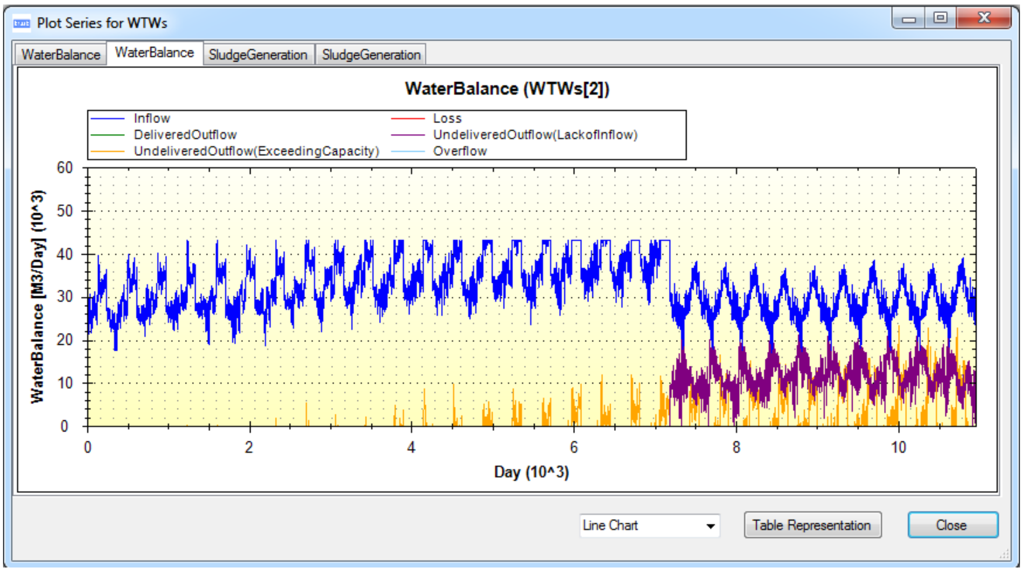


Figure 5 48: Fluctuations of different water flows in Skullerud WTW

Figure 5 49 shows the time series of the sludge generation in Oset WTW in the WaterMet^2 model. As can be seen, the fluctuations of sludge generation are a factor of daily water treatment. Consequently, the sludge generation in this WTW is limited to less than 35,000 kg/day due to limited capacity of the WTW.

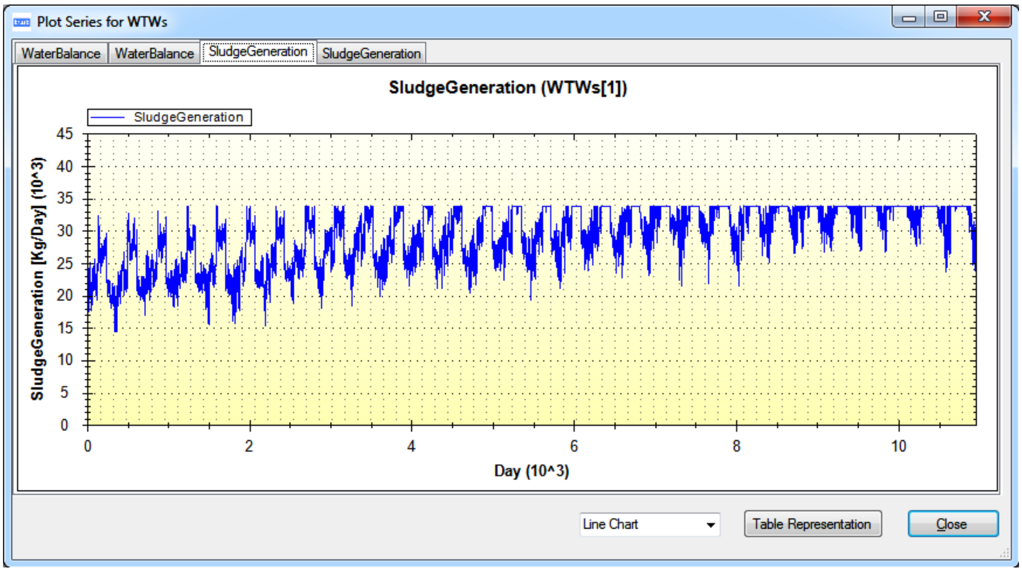
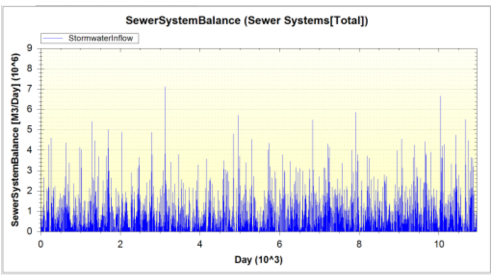
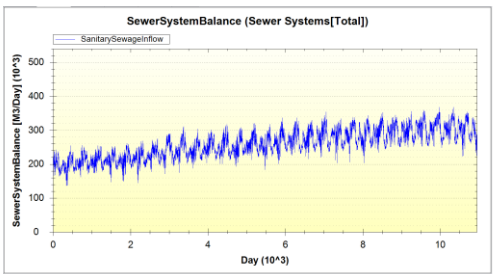


Figure 5 49: Sludge generation in Oset WTW

Figure 5 50 illustrates a number of KPIs related to water and contaminant flows in the sewer system. More specifically, figures (a) and (b) show the inflow to the sewer system as a result of runoff and sanitary sewage, respectively. Given a limited capacity of the sewer system (2.2 million m^3), the sewerage cannot receive the total runoff generated during some of the wet weathers and thus excess flow is envisaged as shown in figures (c) and (e). Furthermore, there are a few CSO occurred in the sewer system discharging into the receiving water. Figure (f) represents the flow of total Nitrogen in sewer system and excess wastewater. Note that the contaminant in excess wastewater reflects the load of contaminant in the surface runoff.



(a)



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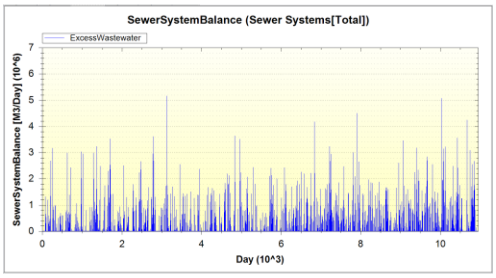
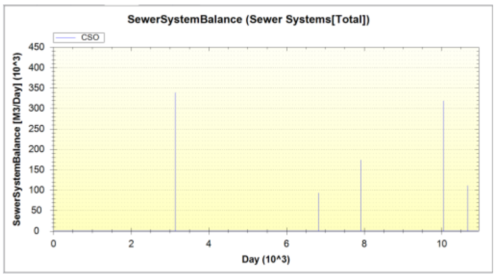


(c)



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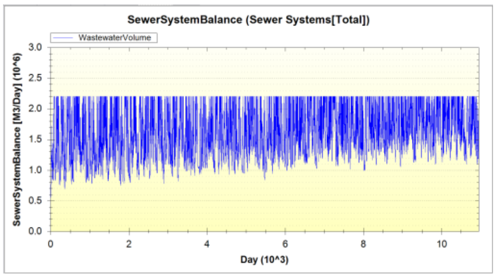

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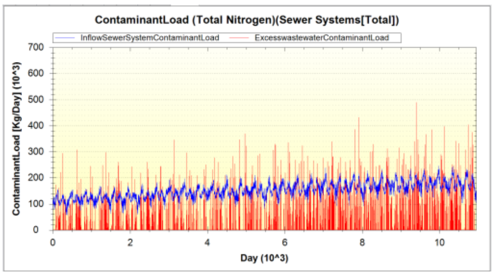
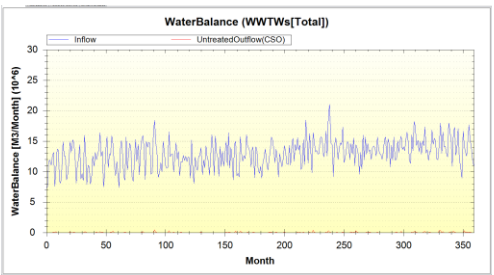


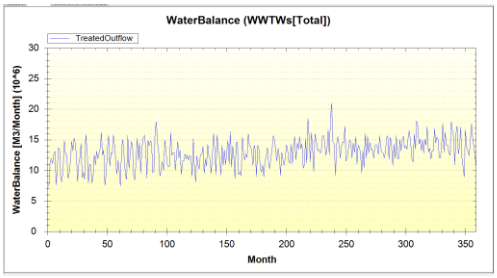
(f)

Figure 5 50:Time series of a number of KPIs in the sewer system (a) runoff inflow; (b) sanitary sewage inflow; (c) excess wastewater; (d) combined sewer overflow; (e) sewer system volume; (f) Total Nitrogen load for inflow and excess runoff.

As an example of available KPIs for the WWTWs in WaterMet^2, Figure 5 51 represents monthly variations of various water flows and annual variations of resource recovery generation and total Phosphorus of water flows in the WWTWs. The variations of monthly untreated outflow from the WWTWs are almost negligible compared to inflow and outflow. The generation of resource recovery in figure c is directly proportional to treated wastewater in figure b.



(a)



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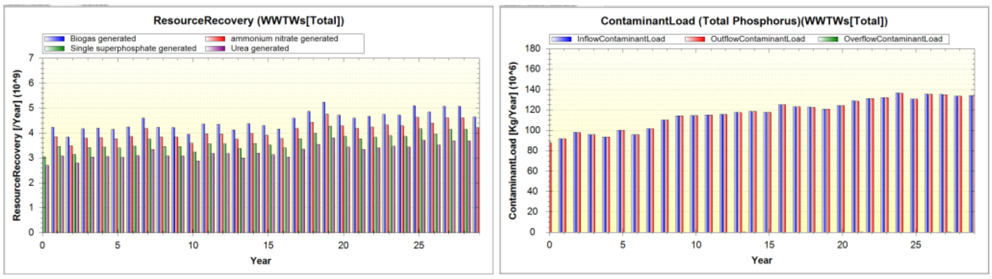
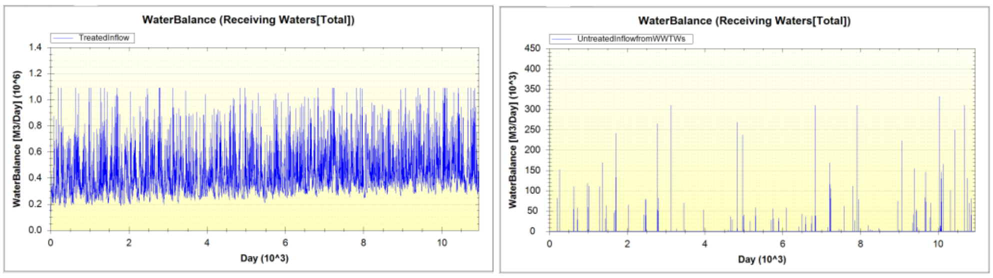


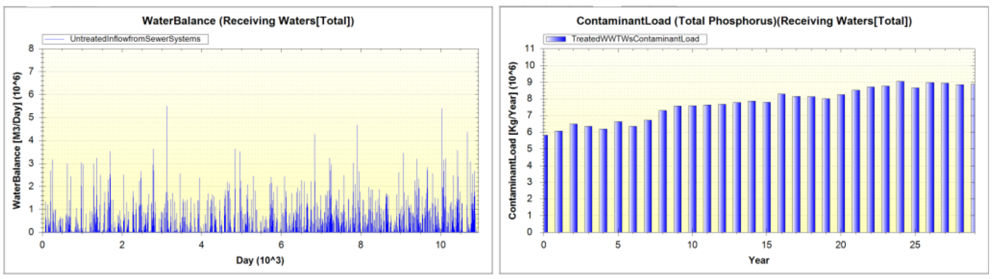
(c) *(d)*

Figure 5 51:Number of available KPIs in WaterMet² for the WWTWs including monthly variation for (a) inflow, untreated outflow and (b) treated outflow; annual variations for (c) resource recovery and (d) total phosphorous flows

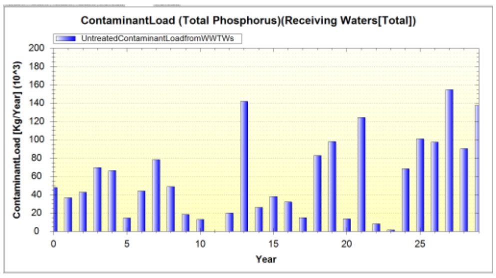
Figure 5 52(a)-(c) represents the daily time series of three different water flows discharged into the receiving water (i.e. Oslo Fjord see Figure 5 1). The simulation shows that total amount of the treated water outflow in the WWTWs into the receiving water fluctuates between 0.2 and 1.1 million m^3/day whilst a number of discharges of untreated wastewater occur in the WWTWs with a maximum of 300,000 m^3/day over the planning horizon. The discharge of excess storm water and CSO into the sea usually happens with a peak value of 5.5 million m^3/day over this period when runoff exceeds the capacity of the sewer system.



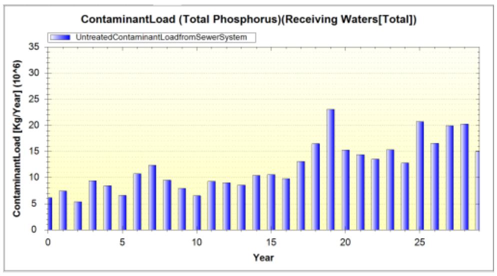
(a) *(b)*



(c) *(d)*



(e)



(f)

Figure 5 52: Water flows discharged into the receiving water from (a) treated wastewater in WWTWs; (b) untreated wastewater in WWTWs; (c) excess storm water and CSO; Total Phosphorus discharged into the receiving water from (d) treated wastewater in WWTWs; (e) untreated wastewater in WWTWs; (f)excess storm water and CSO

As an example of contaminant loads discharging into the sea, Figure 5 52 (d)-(f) depicts the annual variations of total Phosphorus discharged from the three sources into the sea. The treated wastewater contributes a relatively consistent rate in the range between 6 and 9 million kg/year. The highest proportion of total Phosphorus is related to the contaminant load resulted from discharging untreated wastewater and runoff ranging from a minimum of 5 to a maximum of less than 25 million kg/year.

5.5. Modelling Interventions in the UWS

Alternative intervention options are fully analysed under intervention strategies in the DSS as part of WP54 in the TRUST project but they need to be supported and simulated by the WaterMet^2 model. Here, two examples of these intervention options which can be simply constructed in the WaterMet^2 model are presented and the relevant results are analysed. In the first example, adding some new water resources and WTWs are discussed in water supply subsystem. The second example deals with how rainwater harvesting and grey water recycling systems can be added to the UWS model. Note that if an intervention option is going to be added to the UWS at a specific point of time (e.g. at year 5 of the planning horizon), it is necessary that the intervention option is added to the WaterMet^2 model as a dummy element. Then, the element will be active (i.e. in operation) in the WaterMet^2 model at specific time by the relevant intervention strategies controlled by the DSS. More details can be found in the relevant DSS documents in WP54.

5.5.1. Adding new water resources and WTWs

Problem description

In addition to the existing water resources, two potential (new) raw water resources for Oslo city are envisaged in the future as the Holsfjorden Lake (west of Oslo) and the Glomma River (east of Oslo) which are depicted in Figure 5 53. For further details of the existing systems and potential water resources, please refer to the documents 'Rough Analysis of Alternatives' and 'Forecast of Water Usage in the Future in Oslo' and 'Water Treatment Plant Bulletin' (Oslo Water 2011a and b).

Figure 5 53: Layout of both existing and new WTWs and water resources in the UWS

Unlike the limited catchment areas of the existing water resources, the new raw water resources have an unlimited annual capacity of raw water and also inflows into them. As the type of these water resources are classified as surface water, a daily time series of inflow needs to be defined and entered in the 'Time Series' form in WaterMet^2. Therefore, an artificial daily time series with large values (here 2,000,000 m^3/day) is assumed and entered for these additional water resources in the relevant form (not shown here). Similarly, some large values for capacity and initial volume are considered for these water resources in such a way that no water shortage occurs during the planning horizon from these resources (see Figure 5 60a). Water abstraction from these water resources is conducted by pumping systems and hence electricity energy is considered for the conduits connecting to these resources (Figure 5 60a).

When supplying water from new resources in the future, three WTWs may be built in order to comply with the developed UWS (Figure 5 53). They are: (1) WTW for the treatment of raw water withdrawn from the Holsfjorden Lake (WTW3); (2) WTW for the treatment of raw water abstracted from the Glomma River (WTW4); (3) a new Oset WTW for the treatment of raw water from either the Maridalsvannet Lake or the Holsfjorden Lake (WTW5). The specifications of these WTWs which will be used by the WaterMet^2 model are given in the relevant table of 'Asset' tab in Figure 5 60a. Other than the treatment capacity of the new WTWs, other specifications of new WTWs are assumed to be same as the existing WTWs.

To specify the topology of the new elements in the UWS, new flow routes need to be defined based on the intervention options. For adding new water resources, there are four selected alternatives obtained for new raw water resources in the UWS (Oslo Water, 2011a) which are briefly presented as follows:

a) New raw water resource at Holsfjorden Lake and two new WTWs (#3 and #5) described in option 'A2' in the relevant report shown in Figure 5 54.

Figure 5 54: Layout of the water supply subsystem for intervention option A2

b) New raw water resource at Holsfjorden Lake and the two WTWs (#3 and #5) described in option 'A3' in the relevant report shown in Figure 5 55.

Figure 5 55: Layout of the water supply subsystem for intervention option A3

c) New raw water resource at Glomma River and the two WTWs (#4 and #5) described in option 'B2' in the relevant report shown in Figure 5 56.

Figure 5 56: Layout of the water supply subsystem for intervention option B2

d) New raw water resource at Holsfjorden Lake and the two WTWs (#3 and #5) described in option 'C1' in the relevant report shown in Figure 5 57.

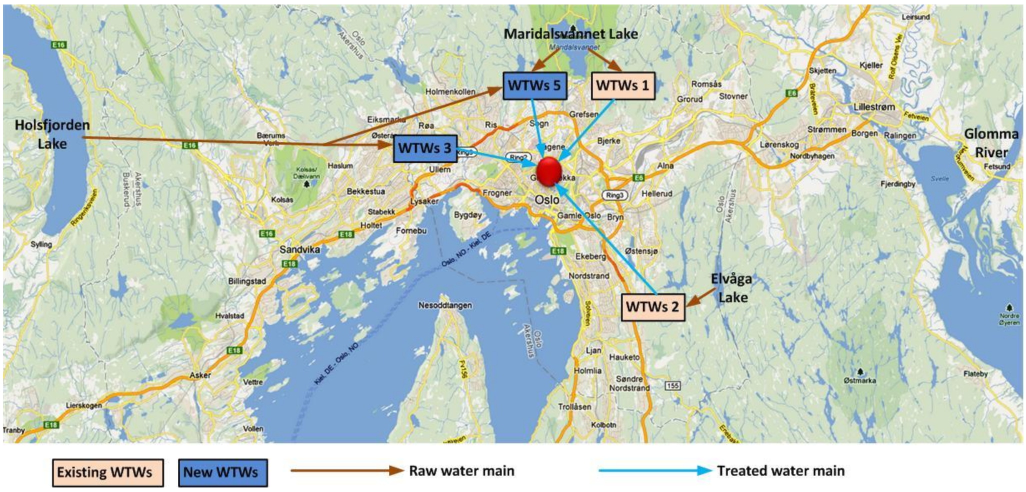


Figure 5 57: Layout of the water supply subsystem for intervention option C1

Setting input data

Note that any of these four intervention option which is selected will be in operation from 2020 which needs to be set out by the DSS. However, the definition of their component and connections in WaterMet^2 are described in this case study. As a result, the topology of all four options of the WSS can be defined as shown in Figure 5 58.

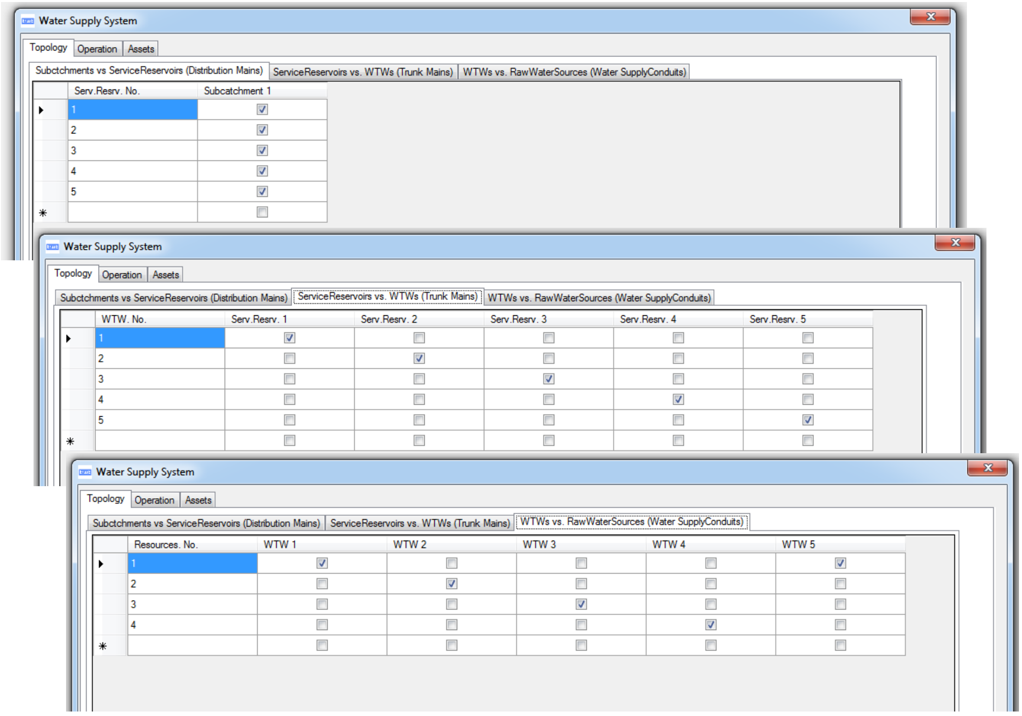


Figure 5 58: Filled 'Topology' tab considering new elements in the WSS

The main difference between these options is how to specify the operation of the WSS when new water resource and WTWs are added. More specifically, percentage split coefficient of water demand for each component needs to be specified for each intervention option. Compared to the existing system which was built in the previous case study, the percentage split coefficient of water demand of the WaterMet^{2}subcatchment from each upstream WTW needs to be specified for new intervention options in the WaterMet^2 model. The percentage split coefficient of the current water demand from the two upstream WTWs is 0.90 and 0.10 for Oset and Skullerud WTWs, respectively (Figure 5 59). If an intervention option including new water resources and WTWs is considered, the percentage split coefficient of water demand for the WaterMet^{2}subcatchment from each upstream WTW needs to be set out according to the capacity of trunk mains connecting water sources to WTWs (Oslo Water, 2011a). These percentage split coefficients are given in Table 5 4.

Table 5 4: Percentage split coefficients of flow of the WaterMet^2 subcatchment from upstream WTWs for each intervention option

NAME OF WTWS	WTWS ID	CURRENT WATER RESOURCES	A2/A3	B2	C1
Oset	1	0.90	0.38	0.38	0.38
Skullerud	2	0.10	0.05	0.05	0.05
Holsfjorden Lake	3	0	0.20	0	0.20
Glomma river	4	0	0	0.20	0
New Oset	5	0	0.37	0.37	0.37

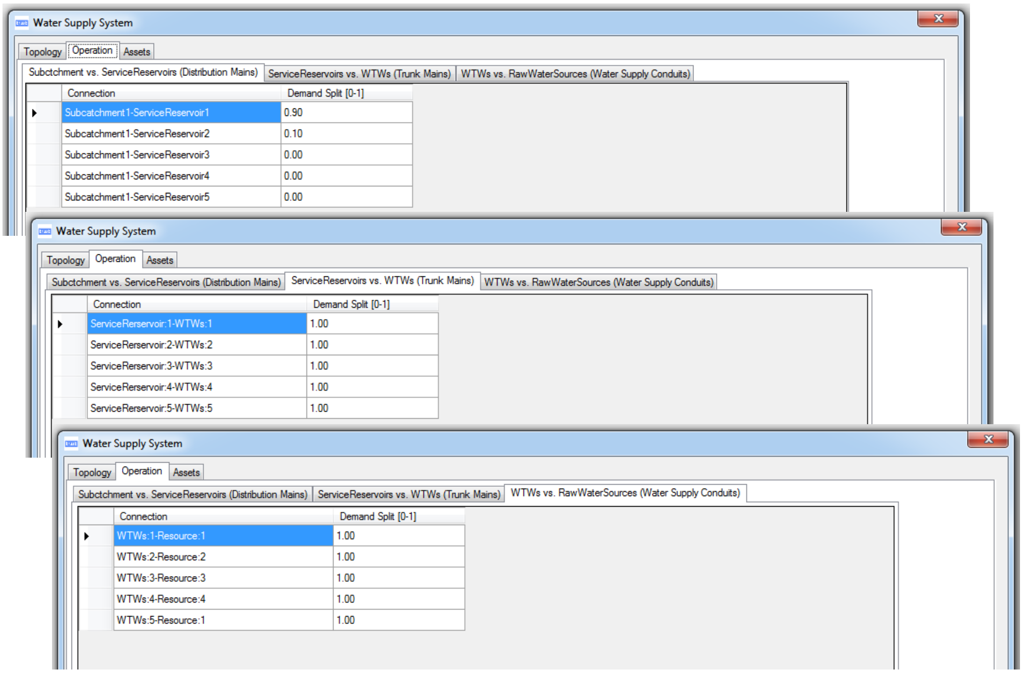
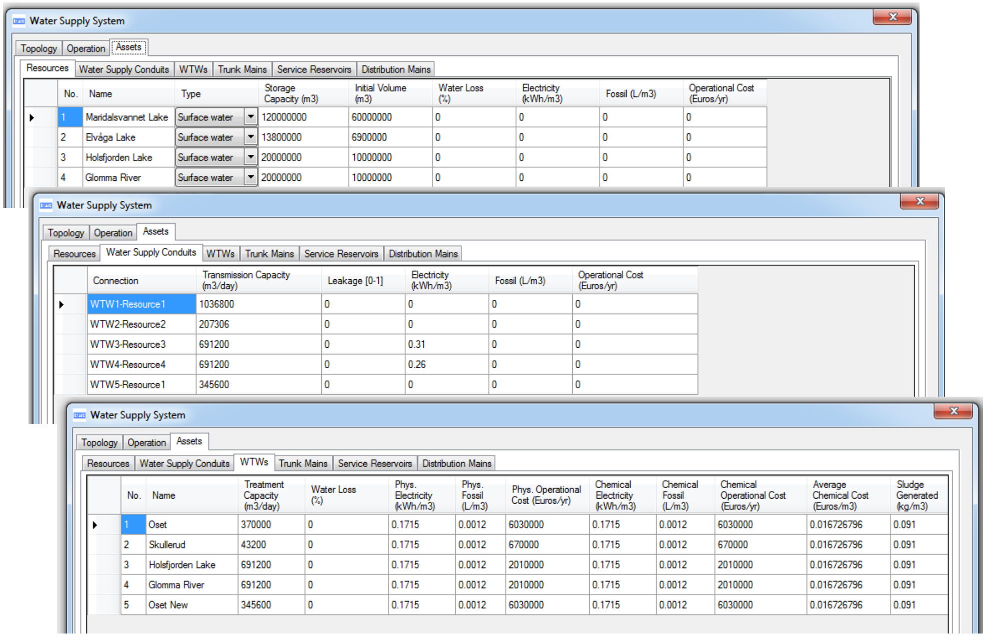
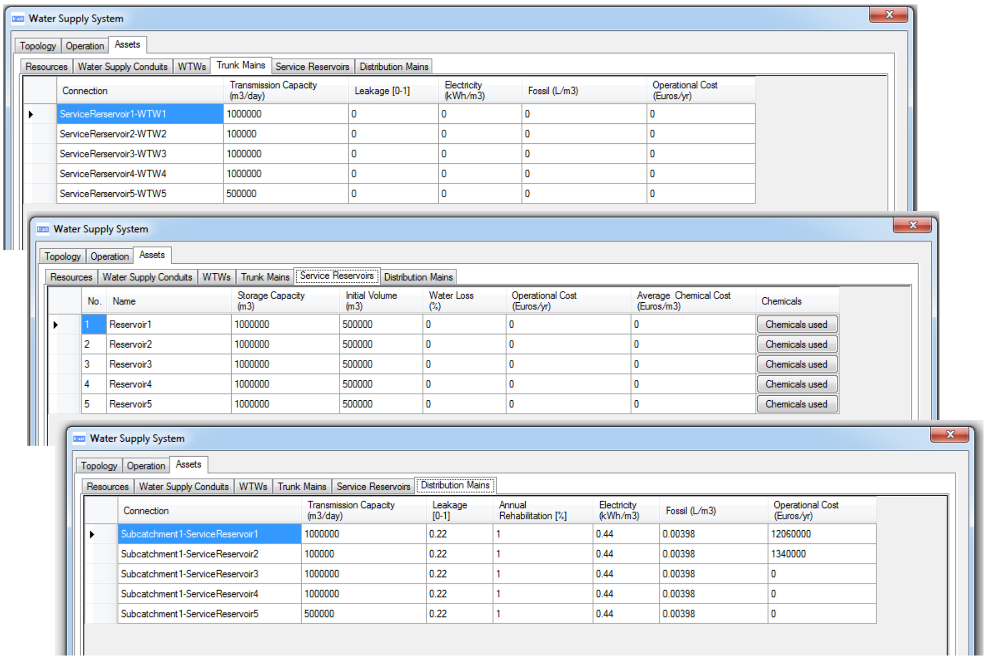


Figure 5 59: Filled 'Operation' tab considering new elements in the WSS

In addition, other specifications of the conduits, trunk mains and distribution mains of the new system in the UWS are populated as shown in Figure 5 60. Note that two conduits are connected to Resource1 since this water resource feeds two WTWs (WTW1 and WTW5) in all options (see Figure 5 54 till 5 57).



(a)

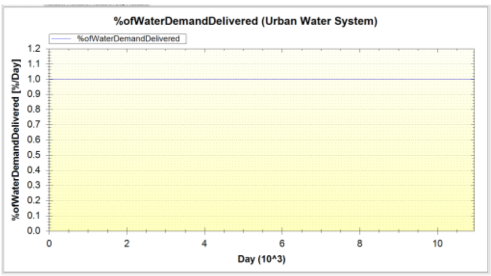


(b)

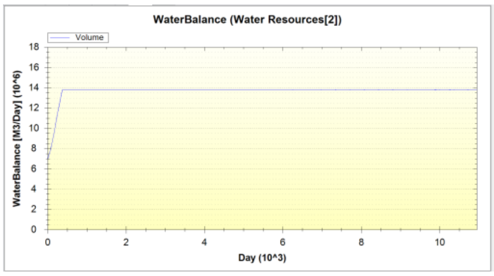
Figure 5 60: Filled 'Assets' tab considering new elements in the WSS for (a) Resources, Conduits and WRWs; (b) Trunk mains, Service Reservoirs and Distribution Mains

Results

By setting the split coefficients in the ‘Operation’ tab of the ‘Water Supply Subsystem’ form for any of the aforementioned intervention options, the new UWS can be ready for analysis in WaterMet^2. The split coefficients of the intervention option A2 specified in Table 5 4 is set out here as an example for this case study. Note that setting the start time for these intervention options can be controlled by thee DSS outside the WaterMet^2 model. Consequently, the new elements in this example are in operation from the first day of the planning horizon.



(a)



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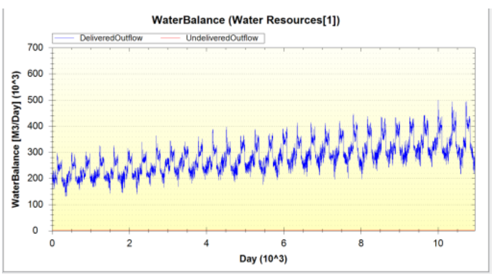

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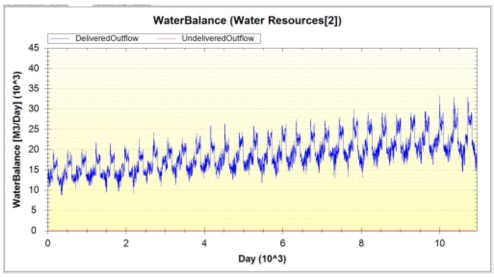

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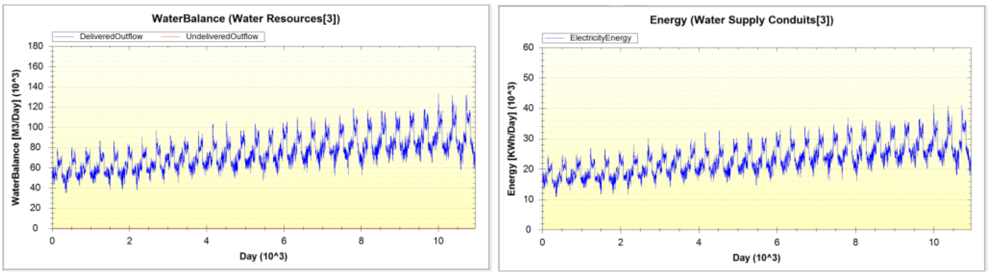


(e) (f)

Figure 5 61: Sample of the result in WaterMet² for the new UWS; daily time series for (a) Percentage of water demand delivered; (b) volume of Elvåga Lake; (c) outflow from Maridalsvannet Lake; (d) outflow from Elvåga Lake; (e) outflow from Holsfjorden Lake; (f) electricity energy consumed by the conduit connected to Holsfjorden Lake;

Some of the available KPIs resulted from the simulation of the WaterMet²model are shown in Figure 5 61. As expected, water demand is fully supplied (100%) in Figure 5 61a compared to Figure 5 37 in which the average is 94% over the planning horizon. Comparing the outflow from the three water resources shows that water abstraction from new water resource 3 (i.e. Holsfjorden Lake) compensate the water shortage mainly due to water resource 2 (i.e. Elvåga Lake). Moreover, no decline is observed in the volume of the Elvåga Lake (Figure 5 61a) compared to emptying the volume of the Lake (Figure 5 46). This compensation will be against the capital costs for new water resource and WTWs as well as the relevant operational costs. As an example, the variations of electricity energy induced by water abstraction from the new water resource are shown in Figure 5 61f.

5.5.2. Adding RWH and RWH systems

Problem description

Other intervention options which can be added to the UWS model in WaterMet² are rainwater harvesting (RWH) and grey water recycling (RWH) systems at any of the local area or subcatchment levels. Adding both RWH and GWR schemes at local area are examined in this case study. Therefore, this intervention option is defined as a combination of one RWH and GWR schemes representing all many small water treatment units across the city assuming that they are adopted by 50% of households. Given that 3 m³ is sufficient for the tank capacity of a household RWH scheme with the capital and operational costs equal to 530 and 24 Euro/m^3 respectively (Ward *et al.* 2010, 2012), the total volume of the single represented RWH tank is 0.48 MCM. Similarly, the size of the represented GWR scheme is assumed to be 39,000 m^3 with EUR 59 million and EUR 1.5 million/year for capital and operational cost respectively (Memon *et al.* 2005). The electricity consumption of RWH and GWR schemes is assumed to be 0.54 and 1.84 kWh/m^3 respectively (Ward *et al.* 2011, Memon *et al.* 2005).

Setting input data

The first step of setting input data is to allocate recycling water to various water demand profiles in the WaterMet^2 model which is shown in Figure 5 62. Here, it is assumed that both types of recycling water (i.e. from RWH and GWR schemes) can only be used for toilet, industrial and irrigation water demands. The second step is to define the specifications of the two systems located in the single local area which is show in Figure 5 63 and Figure 5 64 for RWH and GWR schemes, respectively. General specifications of these two systems are defined as outlined above. In both systems, the start year in operation is set for year 5 of the planning horizon. Similar to water allocation, the specific use of stored water in both systems are considered for toilet, industrial and irrigation water demands. Also, it is assumed that the RWH scheme collects the runoff from both impervious areas (i.e. roof and paved & road surfaces) and overflow is discharged into the local area grey water recycling tank. The GWR scheme collects grey water from hand basin, shower, dish washer, washing machine and frost tapping. Finally, the pollutant removal in both systems for all contaminant types is assumed to be 95%.

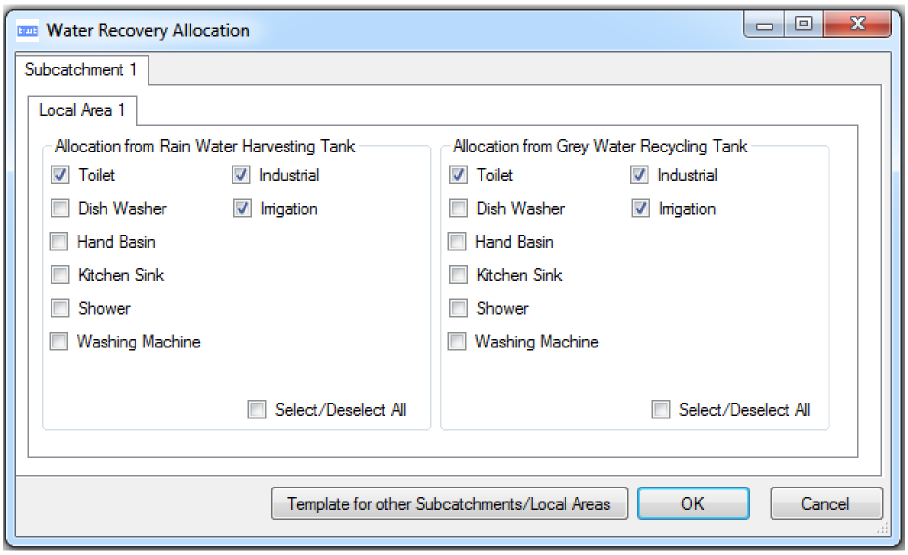


Figure 5 62: Allocation of recycling water for water demand profile in the UWS model

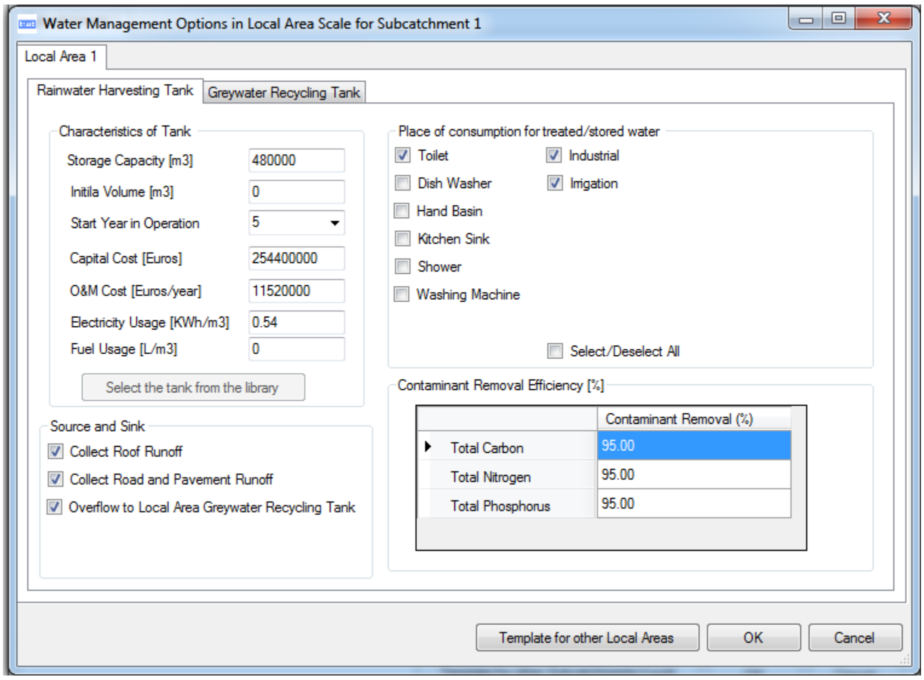


Figure 5 63: Specification of the proposed RWH scheme for the UWS model

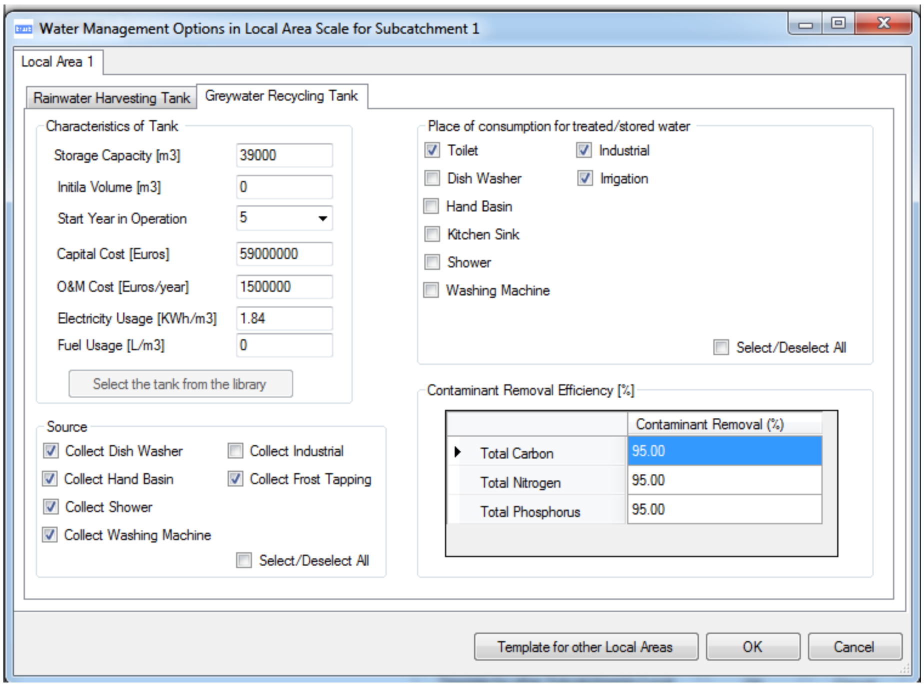
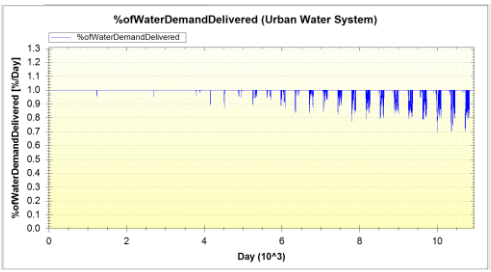


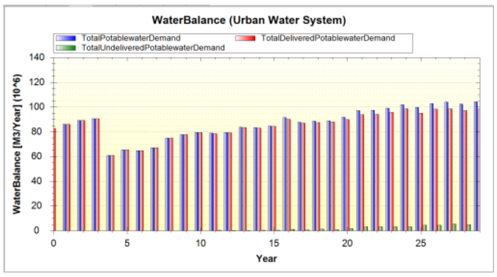
Figure 5 64: Specification of the proposed GWR scheme for the UWS model

Results

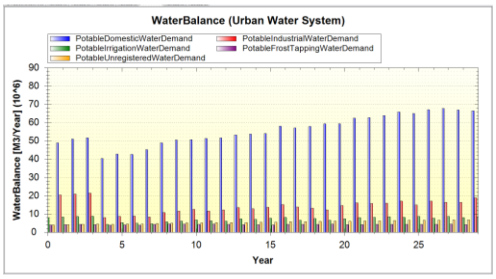
Figure 5 65 shows some examples of the available KPIs in WaterMet^2 for the UWS model. As seem in Figure 5 65a, the percentage of delivered water demand has improved compared to business as usual in Figure 5 37. This is because two additional water sources (i.e. grey water and rain water) are available to supply water demand profiles instead of only potable water source. More specifically, water supply by potable water declines after year 5 (Figure 5 65b) because some water demand categories especially industrial and indoor water are supplied by the two new water sources (see Figure 5 65c-f). Comparing between Figure 5 65e and Figure 5 65f shows that the recycling water are more provided by the RWH tank as water supply by local area RWH tank has a higher priority over local area GWR tank. As a result, most of the volume of the collected grey water (around two third) can be envisaged as useless volume (Figure 5 65d). The tank volume and other KPIs of the water treatment options can be further improved by applying a sensitivity analysis or coupling some optimisation model with the WaterMet^2 model. To do the latter, the optimisation model can be linked to the WaterMet^2 model through a series of Toolkit functions outlined in the previous chapter.



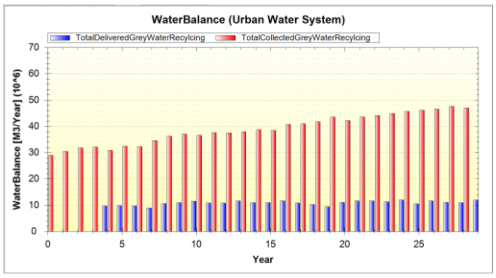
(a)



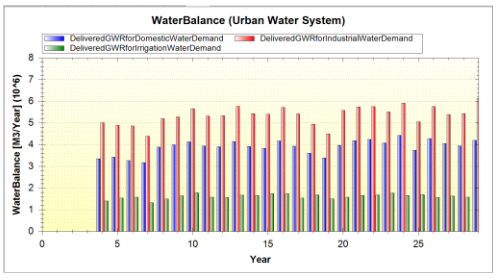
(b)

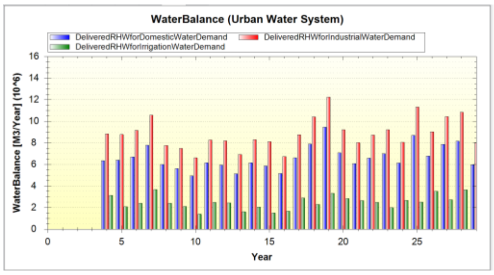


(c)



(d)





(e) *(f)*

Figure 5 65: Some examples of KPIs resulted from adding water recycling schemes in the UWS model.

6. Summary and Conclusions

This report presented the methodology and software tool of the WaterMet^2 model to cover both research and practical aspects of the model, respectively. The modelling concepts including spatial &temporal resolutions, principal flows and the relevant mass balance equations were described by the methodology. Also, different modules of the tool were described in more detail ranging from software installations and input forms to running a simulation, model calibration and retrieving outputs. The WaterMet^2 was then illustrated for modelling the UWS of the city of Oslo in Norway, as a reference city, in which input data preparation, forms' population and samples of the results were described. The case study was analysed for two states including the existing conditions and modelling of some interventions.

Based on the report and the analyses in the case study, the following conclusions can be drawn:

1. The new WaterMet^2 methodology and the corresponding software tool can and should be used for the strategic-level planning of the future UWS. The level of detail modelled may not be able to provide the detailed list of interventions to be implemented but it will definitely help identify the most promising transition path(s) into the longer-term future. The 'big picture' type information generated in this way can then be used as an input to the next (tactical/detailed) level of planning.
2. It is important to assess the long-term UWS performance by using a range of different evaluation criteria, both quantitative and qualitative. The WaterMet^2 model enables the calculation of most quantitative UWS performance criteria values with particular strengths in estimating the sustainability type criteria - in addition to more conventional performance criteria.
3. WaterMet^2 as an integrated modelling tool in UWS enables the planners to track down the long-term impact of intervention options on both water supply and wastewater subsystems simultaneously. This would result in recognising not only the shortcomings of the existing conditions but also the intervention options which improves the overall performance of both water supply and wastewater subsystems. Therefore, it is important to model the full urban water cycle in an integrated fashion as the resulting best long-term intervention strategy(ies) can be quite different when compared to the corresponding best intervention strategies identified by considering only part of the urban water cycle (e.g. WSS here).

Modelling of the existing conditions and some interventions for the UWS described in chapter 5 is for illustrative purposes only, i.e. with the aim of demonstrating some resulting KPIs obtained by using WaterMet^2. However, further illustration of WaterMet^2 capabilities can be seen by either building a distributed WaterMet^2 model of the UWS (e.g. multiple subcatchments) or modelling more intervention options. Modelling intervention strategies will be carried out by the DSS as part of WP54. Further to the KPIs available in WaterMet^2, other KPIs which can be built based on the available KPIs can be investigated in WaterMet^2. This will be more investigated for risk type KPIs in WP32. Moreover, further testing and verification on other real-life UWS are also recommended. Further methodological developments for modelling different components in WaterMet^2 are also recommended.

Although WaterMet^2 strives to overcome the drawbacks of the physically based model and the previously developed conceptually based model, it still has some issues which need to be regarded when analysing an UWS. The main issue is related to the time step of modelling in WaterMet^2 (i.e. daily) when compared to physically based models (e.g. hourly and less than it). This has led to some other issues in WaterMet^2. One of them is to simplify some processes such as hydraulic and water quality routing. For instance, system pressures cannot be modelled and water pollutants are analysed and expressed as pollutant fluxes rather than concentrations due to the fact that daily time step cannot provide enough accuracy for travel time of water quality routing. Such a simplification is considered inevitably for other similar conceptually based models. Therefore, calculation of any KPIs which needs less than one day cannot be captured by the WaterMet^2 model.

Despite these shortcomings, the WaterMet^2 model and its demonstration here showed that this model is a capable tool for strategic assessment of an integrated UWS which quantifies sustainability performance criteria. Therefore, this tool can be specifically used for comparison of different management approaches in an UWS at the strategic level of planning. When combing with other multi-criteria decision analysis tools such as the DSS, this tool can be used for planning and management of UWS by a wide range of stakeholders involved.

Finally note that the reference city modelled here by WaterMet^2 is not fully representative for Oslo City in Norway. It was used for the purpose of understanding significant relationships among the entities of UWS, to illustrate the main drivers potentially impacting on UWS and for illustrative purposes that how WaterMet^2 can be applied for modelling a real-life UWS. Hence, the analysis conducted and the corresponding results obtained in this report do not reflect the views of the Oslo VAV and have been used only to demonstrate possible application and functionality of the WaterMet^2 simulation model and software tool.

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8. Appendices

8.1. Appendix A: Embodied energy

Embodied energy and associated GHG emissions are given below for categories of materials, chemicals, energy source and by-products (Venkatesh 2011). In the WaterMet^2 model, materials will be used in pipeline rehabilitations and chemicals will be used in WTWs.

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

NAME OF CHEMICALS	EMBODIED ENERGY (KWH/KG)	GHG EMISSIONS (KG CO_2-EQ/KG)	ACIDIFICATION (KG-SO_2/KG)	EUTROPHICATION (KG-PO_4-EQ/KG)
PVC pipe	0.9	2.36	0.00725	0.00087
PE pipe	0.9	2.34	0.0179	0.00382
Mild steel pipe	26.67	6.5	0.00605	0.0115
Ductile iron pipe	10.56	3.4	0.0166	0.00173
Grey cast iron pipe	6.94	3.34	0.0163	0.0169
Concrete	0.1	0.125	0.00024	0.0000796
Epoxy resin	6.39	6.7	0.04	0.0064
Polyurethane	0.49	4.3	0.00853	0.00308
Copper	5.56	2.33	0.141	0.166
Polypropylene	0.73	1.16	0.00516	0.00308

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

NAME OF CHEMICALS	EMBODIED ENERGY (KWH/KG)	GHG EMISSIONS (KG CO_2-EQ/KG)	ACIDIFICATION (KG-SO_2/KG)	EUTROPHICATION (KG-PO_4-EQ/KG)
Alum ($AL_2(SO_4)_3$)	0.89	0.49	0.0101	0.00141
Carbon dioxide (CO_2)	1.4	0.794	0.00204	0.00109
Calcium hydroxide ($Ca(OH)_2$)	1.0	0.763	0.00069	0.00016
PAX	2.79	1.14	0.00606	0.00319
Sodium hypochlorite (NaoCl)	6.0	5.63	0.0277	0.0173
Chlorine	1.0	1.05	0.0529	0.00356
Iron (Ferric) chloride	1.39	0.26	0.00424	0.0291
Iron (Ferric) sulphate	2.0	0.37	0.00093	0.000085
Nitric acid	3.31	6.3	0.0173	0.00428
Methanol	4.56	0.736	0.00125	0.00040
Ethanol	0.83	1.23	0.00361	0.00171
Sodium hydroxide	0	2.18	0.0107	0.0074
Potassium permanganate	2.16	1.16	0.00516	0.00308
Ozone	15.58	7.99	0.0384	0.0267
Silica sand/Microsand	0.06	0.021	0.0000582	0.0000105

Table A.3: Embodied energy and associated GHG in energy sources

NAME OF ENERGY SOURCE	EMBODIED ENERGY (KWH/KG)	GHG EMISSIONS (KG-CO_2/-EQ/KWH IN ELECTRICITY AND KG-CO_2-EQ/KG IN FUELS)	ACIDIFICATION (KG-SO_2/-EQ/KWH IN ELECTRICITY AND KG-SO_2-EQ/KG IN FUELS)	EUTROPHICATIO N (KG-PO_4-EQ/KWH IN ELECTRICITY AND KG-PO_4-EQ/KG IN FUELS)
Electricity	-	0.21	0.00049	0.000156
Fossil fuel (diesel)	12	3.99	0.0106	0.000848
Coal	8	2.94	0.0239	0.000985
Fuel oil	11.39	3.77	0.0168	0.00136
Gasoline	13.33	3.66	0.0286	0.0059
LPG	12.9	3.59	0.00753	0.000778

Natural gas	10.6	3.4	0.0343	0.000421
Wood	4.17	0.00024	0.00000173	0.000000321

Table A.4: Embodied energy, GHG, acidification and eutrophication in by-products

NAME OF BY-PRODUCT	EMBODIED ENERGY (KWH/KG)	GHG EMISSIONS (KG-CO_2-EQ/KG)	ACIDIFICATION (KG-SO_2/KG)	EUTROPHICATION (KG-PO_4-EQ/KG)
Ammonium nitrate	2.72	2.97	0.00237	0.00843
Single superphosphate	0.575	0.548	0.00248	0.00941
Urea	4.81	1.52	0.0175	0.00579

8.2. Appendix B: Energy cost

The cost of energy in the form of either electricity or fossil fuel, which will be used in the WaterMet^2 model is given in Table B.1.

Table B.1: Cost of energy sources

NAME OF ENERGY SOURCE	COST
Electricity	0.0854 (Euro/kWh)
Fossil fuel (diesel)	1.15 (Euro/Litre)

8.3. Appendix C: Specification of rehabilitation methods

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

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

SIZE OF PIPELINE	TOTAL COST (EURO/M)	DIESEL CONSUMPTION (LITRE/M)
Small-size pipeline (diameter<249 mm)	275	1.0
Medium-size pipeline (250 mm<diameter<449 mm)	526	1.5
Small-size pipeline (500 mm<diameter)	1242	2.0

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

METHOD OF REHABILITATION	% OF TOTAL ANNUAL REHABILITATION	COST (COEFFICIENT OF THE COST FOR SLIP-LINING WITH PE PIPE)	GHG EMISSIONS (COEFFICIENT OF THE GHG EMISSIONS FORSLIP-LINING WITH PE PIPE)
lining with polyurethane (PU)	40	0.5	0.5
slip-lining with PE pipe	20	1	1
pipe cracking + lining	20	1.5	1.5
rebuilding with ductile iron pipe	20	5	10

8.4. Appendix D: Examples of WaterMet^2 Toolkit functions

Once a WaterMet^2 model is built by stand-alone WaterMet^2 tool and saved as WaterMet^2 input file (i.e. in this appendix as “Oslo WM2.xml”), it can simply be called within other programming languages by WaterMet^2 Toolkit functions to develop any specific and customised applications. In this appendix, an example of calling the WaterMet^2 model within three widely used programming languages (i.e. C# .NET, VB .NET and MATLAB) is demonstrated. Here, only some examples of using the toolkit functions are presented but for a full list of WaterMet^2 toolkit functions, the reader is referred to the toolkit function report (Behzadian and Kapelan 2014) or the relevant chm file.

In the example presented below by three programming languages, a WaterMet^2 input file known as “Oslo WM2.xml” is first opened. Then, it is intended that electricity energy for water abstraction from all water resources is increased annually by 10%. Note that the model is simulated for a 30 year planning horizon. Finally, four time series of daily results over the planning horizon are retrieved as: percentage of water demand delivered, electricity used, water demand and water supply.

8.4.1. C# .NET example

To call a WaterMet^2 model in C# .NET Visual Studio using toolkit.dll, it is first necessary to add Toolkit.dll to the reference list. Then, the following source code can be used for handling the abovementioned problem which is created in a Windows Form of C# .NET Visual Studio.

```
usingToolkitns;

namespaceWindowsFormsApplication
{
publicpartialclassForm1 :Form
    {
public Form1()
        {
InitializeComponent();
        }
intNoDaysTimeStep;
intNoTimeSteps;
privatevoid button1_Click(object sender, EventArgs e)
        {
NoDaysTimeStep=Convert.ToInt32(NoDaystextBox.Text);
NoTimeSteps = Convert.ToInt32(NoTimeStepstextBox.Text);
Toolkitns.Toolkit.FileStream("Oslo WM2.xml",
"C:\\WindowsFormsApplication\\bin\\Debug\\", 1);
Toolkit.SimulateInitial();// this function needs to be called before
start of the simulation
intNResources = Toolkit.GetAssetNo(1);//number of resources
// Run the loop of simulation
for (inti = 0; i< 10950; i++)
            {
Toolkit.SimulateTimeStep(i);// this function simulates the waterMet2
model for day i
if (i % 365 == 0 &&i != 0)
for (int j = 0; j <NResources; j++)
Toolkit.SetAssetWSS(1, 2, j + 1, Toolkit.GetAssetWSS(1, 2, j + 1) *
1.10);//' assuming that each year the electricity of the resources will
increase by 10%. Therefore this
//' function first retrieve the electricity of each source and then set
it to the value of interest
            }
```

```
string q = Toolkit.PreparingFillTimeStep(1, 0, NoDaysTimeStep);// After
simulating the model, to prepare the result in the format of specific
aggregated time step(e.g. 1 for daily,
// 7 for weekly and 30 for monthly, 365 for annually, and 0 for the whole
planning horizon)
if (q != "")
MessageBox.Show("Please check the parameters of the functions in the
code!", "Error Message", MessageBoxButtons.OK, MessageBoxIcon.Error,
MessageBoxDefaultButton.Button1);

// Get some samples of the results
double[] PercentWaterDelivered = newdouble[NoTimeSteps];
Toolkitns.Toolkit.GetKPIsTimeSeries(refPercentWaterDelivered, 7, 1, 20,
0);//' for retrieving percentage of water demand delivered
double[] ElectUsed = newdouble[NoTimeSteps];
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(refElectUsed, 34, 0);//for
retrieving electricity used
double[] WaterDemand = newdouble[NoTimeSteps];
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(refWaterDemand, 0, 0);//for
retrieving water demand
double[] WaterSupply = newdouble[NoTimeSteps];
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(refWaterSupply, 1, 0);//for
retrieving water supply
MessageBox.Show("Calculation finished!", "Information",
MessageBoxButtons.OK, MessageBoxIcon.Information,
MessageBoxDefaultButton.Button1);
        }
    }
}
```

8.4.2. VB .NET example

Similar to C# .NET Visual Studio, to call a WaterMet^2 model using toolkit.dll in VB .NET Visual Studio, it is also necessary to add Toolkit.dll to the reference list in advance. Then, the following source code can be used for handling the abovementioned problem which is created in a Windows Form of VB .NET Visual Studio.

```
ImportsToolkitns
PublicClassForm1
PrivateNoDaysTimeStepAsInteger
PrivateNoTimeStepsAsInteger
PrivateSub Button1_Click_1(sender AsSystem.Object, e AsSystem.EventArgs)
Handles Button1.Click
NoDaysTimeStep = Convert.ToInt32(NoDaystextBox.Text)
NoTimeSteps = Convert.ToInt32(NoTimeStepstextBox.Text)
Toolkitns.Toolkit.FileStream("Oslo WM2.xml",
"C:\WindowsApplication\bin\Debug\", 1)
Toolkit.SimulateInitial() ' this function needs to be called before start
of the simulation
DimNResourcesAsInteger = Toolkit.GetAssetNo(1) ' number of resources
DimiAsInteger = 0
' Run the loop of simulation
Whilei< 10950
Toolkit.SimulateTimeStep(i) ' this function simulates the waterMet2 model
for day i
```

```
IfiMod 365 = 0 AndAlsoi<> 0 Then
Dim j AsInteger = 0
While j <NResources
Toolkit.SetAssetWSS(1, 2, j + 1, Toolkit.GetAssetWSS(1, 2, j + 1) * 1.1)
' assuming that each year the electricity of the resources will increase
by 10%. Therefore this
' function first retreive the electricity of each source and then set it
to the value of interest
System.Math.Max(System.Threading.Interlocked.Increment(j), j - 1)
EndWhile
EndIf
System.Math.Max(System.Threading.Interlocked.Increment(i), i - 1)
EndWhile
Dim q AsString = Toolkit.PreparingFillTimeStep(1, 0, NoDaysTimeStep) '
After simulating the model, to prepare the result in the format of
specific aggregated time step(e.g. 1 for daily,
' 7 for weekly and 30 for monthly, 365 for annually, and 0 for the whole
planning horizon)
If q <>""Then
MessageBox.Show("Please check the parameters of the functions in the
code!", "Error Message", MessageBoxButtons.OK, MessageBoxIcon.[Error],
MessageBoxDefaultButton.Button1)
EndIf

' Get some samples of the results
DimPercentWaterDeliveredAsDouble() = NewDouble(NoTimeSteps) {}
Toolkitns.Toolkit.GetKPIsTimeSeries(PercentWaterDelivered, 7, 1, 20, 0) '
for retrieving percentage of water demand delivered
DimElectUsedAsDouble() = NewDouble(NoTimeSteps) {}
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(ElectUsed, 34, 0) ' for retrieving
electricity used
DimWaterDemandAsDouble() = NewDouble(NoTimeSteps) {}
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(WaterDemand, 0, 0) ' for
retrieving water demand
DimWaterSupplyAsDouble() = NewDouble(NoTimeSteps) {}
Toolkitns.Toolkit.GetKPIsTimeSeriesUWS(WaterSupply, 1, 0) ' for
retrieving water supply
MessageBox.Show("Calculation finished!", "Information",
MessageBoxButtons.OK, MessageBoxIcon.Information,
MessageBoxDefaultButton.Button1)
EndSub

PrivateSubNoTimeStepstextBox_TextChanged(sender AsSystem.Object, e
AsSystem.EventArgs) HandlesNoTimeStepstextBox.TextChanged

EndSub

PrivateSubNoDaystextBox_TextChanged(sender AsSystem.Object, e
AsSystem.EventArgs) HandlesNoDaystextBox.TextChanged

EndSub
EndClass
```

8.4.3. MATLAB example

The following source code can be used in MATLAB software tool to call the WarerMet[2] model. Eventually all four time series results are drawn in each quarter of a presenting plot.

```
NET.addAssembly('C:\Toolkit files\Toolkit.dll');
WM1=Toolkitns.Toolkit;
WM1.FileStream('OsloWM2.xml', 'C:\\WM2 Input Folder', 1);
WM1.SimulateInitial();
m=10950;
NResources=WM1.GetAssetNo(1);
fori=1:m
WM1.SimulateTimeStep(i);
if(mod(i,365)==0 &&i~=1)
for j=1:NResources
WM1.SetAssetWSS(1,2,j,WM1.GetAssetWSS(1,2,j)*1.10);
end
end
end
Rv=char(WM1.PreparingFillTimeStep(1,0,1));
if(strcmp(Rv,'')==0) Rv
end
n=10950;
x=1:n;
d1 = NET.createArray('System.Double',n);
[Rv,d1] = WM1.GetKPIsTimeSeries(d1, 7, 1, 20, 0);
d2 = NET.createArray('System.Double',n);
[Rv,d2] = WM1.GetKPIsTimeSeriesUWS(d2, 21, 0);
d3 = NET.createArray('System.Double',n);
[Rv,d3] = WM1.GetKPIsTimeSeriesUWS(d3, 34, 0);
d4 = NET.createArray('System.Double',n);
[Rv,d4] = WM1.GetKPIsTimeSeriesUWS(d4, 0, 0);
d5 = NET.createArray('System.Double',n);
[Rv,d5] = WM1.GetKPIsTimeSeriesUWS(d5, 1, 0);
subplot(2,2,1); plot(d1)
subplot(2,2,2); plot(d2);
subplot(2,2,3); plot(d3);
subplot(2,2,4); plot(x,d4,x,d5);
```

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