Scenario 2040
for Oslo as model city

GOVINDARAJAN VENKATESH
SVEINUNG SÆGROV
HELGE BRATTEBØ

trust

D34.2

TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

ABSTRACT

This report – **D34.2,** authored by NTNU, is a sequel to **D34.1** in which interventions suggested by the water-sanitation utility in Oslo - Oslo *Vann og Avløpsetaten,* had been tested using both the models – the WaterMet 2 (WM^2) model developed by Exeter and the Dynamic Metabolism Model (DMM) developed at NTNU, as part of TRUST.

The report starts off by emphasising the need for a holistic long-term sustainability approach in decision-making in water and wastewater utilities around the world. The models referred to above, are proposed as aids in meeting this need. With the help of references to earlier published works and TRUST deliverables related to these models, as well as some new tests carried out using one of them (DMM), the usability of the same has been demonstrated. 'Usability' here refers to understanding the impact of interventions on selected metrics/indicators in year-2040 (in keeping with the title of the deliverable; and the timeframe which has been considered for the TRUST project); and subsequent choices/selections which utilities would like to make depending on their priorities, targets and benchmarks they would set for themselves. As concluded in D34.1, there are differences between WM^2 and DMM – which make them useful in different contexts – situational, circumstantial etc. These differences are recounted here again, in order to make it clear to the readers and end-users that one model is not meant to substitute the other, per se. Simply put, depending on what the end-users' needs, goals, objectives and constraints are, one or the other would be preferable.

The models have been extensively tested at Oslo VAV. A brief summary of the initial feedback from personnel at Oslo VAV is provided. The models were also introduced to pilot cities to understand their points of view, which have been presented in brief.

Keywords

WaterMet^2 (WM^2), Dynamic Metabolism Model (DMM), Urban water system (UWS), Key Performance Indicators (KPIs), Weighting, PLAN, Oslo VAV, Greenhouse gas emissions, Energy consumption

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1. INTRODUCTION

Urban water services are increasingly paying more attention to decision-making based on multiple objectives these days - water safety, climate change adaptation and mitigation, environmental life cycle assessment (LCA), total cost efficiency, inter alia. The greater the diversity of objectives, the more important it becomes to incorporate sustainability into the so-called ‘mission statement’ of the utility. Sustainability, by definition is trying to reconcile among conflicting goals and needs, and doing so without missing the wood for the trees or vice versa for that matter. Sustainability, essentially, is what one may label as a ‘right-brain’ concept, which arises out of awareness and visualization (the understanding of it can be dubbed as an ‘art’ if one may); but unless translated into ‘left-brain’ logic, structures, approaches and implementable ideas, it remains a vague philosophical construct. The said translation entails the introduction of measurements – numbers essentially – into the fray. The path towards sustainability needs to be charted out in a stepwise fashion and there need to be concrete ways to ensure whether one is on the right path or barking up the wrong tree! It is here that metrics and indicators are handy. In other words, Key Performance Indicators (KPIs). Gathering data (systematic monitoring, measuring and recording), managing them, structuring databases, and using the data to obtain values for these KPIs, is important in this regard. This cannot be dispensed with. There are no quick fixes.

The two models - DMM and WM2 - which are presented in this deliverable (and were also presented in D34.1) are enablers of this ‘translation’. They are mass-balance-based, metabolism-centred models (with some differences in structure and outputs, which will be discussed later). They use recorded data, and convert them into suitable metrics / indicators, some of which can subsequently be fed into a Decision-Support-System which as the name suggests, enables utilities in decision-making with an eye on sustainability. The stress here is on ‘some’. We are referring to the intersection set of the outputs of both models, and the all the input requirements for the DSS, as far as indicators are concerned. Some of the sustainability criteria (as defined in the deliverable by Brattebø et al (2011)) are not addressed in the DMM and WM2, and need to be addressed by other means. This is also true for some indicators in the criteria which are addressed in the models. Utilities however, may wish to add on some metrics from outside the intersection set, calculated using the DMM and/or WM2, in their decision-making...in cases where contexts and differences in operation demand that an indicator or more, from outside the intersection set, be included.

In this deliverable, with the help of references to earlier published works and TRUST deliverables related to these models, referred below as appropriate (and also some other general works pertaining to urban metabolism, metabolism in water and wastewater utilities), as well as some new tests carried out using one of them (DMM), the usability of the same has been demonstrated. 'Usability' here refers to understanding the impact of interventions on selected metrics/indicators in year-2040 (in keeping with the title of the deliverable; and the timeframe which has been considered for the TRUST project); and subsequent choices/selections which utilities would like to make depending on their priorities, targets and benchmarks they would set for themselves. As concluded in D34.1, there are differences between WM^2 and DMM – which make them useful in different contexts – situational, circumstantial etc. These differences are recounted here again, in order to make it clear to the readers and end-users that one model is not meant to substitute the other, per se. Simply put, depending on what the end-users' needs, goals, objectives and constraints are, one or the other would be preferable.

The models have been extensively tested at Oslo VAV. A brief summary of the feedback from personnel at Oslo VAV is provided. The models were also introduced to pilot cities to understand their points of view, which have been presented in brief.

2. LITERATURE REVIEW

Different systems-analysis methods and models have been widely used in the last few decades in order to examine biophysical patterns of urban systems and infrastructures at different spatial and temporal scales (Venkatesh, Brattebø and Sveinung, 2014). Among these, the methods of material flow analysis (MFA) and life cycle assessment (LCA) today represent common approaches. Brunner et al (2004) stressed on the usefulness of MFA in urban metabolism studies and urban planning. Brattebø et al. (2009) proposed a dynamic MFA model for built environment applications, and illustrated its usefulness to both historical analyses and forecasts for the future. Kennedy et al. (2011) charted out a history of urban metabolism studies (including urban water issues) and maintained that such studies have practical applications to urban designers and planners as an adaptive approach to technological and socio-political solutions and their consequences.

Integrated modelling of urban water systems has been around for some time now, as evidenced by such models as *Aquacycle* (Mitchell et al., 2001), *UWOT* (Makropoulos et al., 2008), *UVQ* (Mitchell and Diaper, 2010) and *CWB* (Mackay and Last, 2010). The DMM and the WM2 are not proposed as an alternative to any of the existing integrated models. They are tailor-made to fulfil specific end-goals, and thereby certainly do have their own applicability constraints.

Venkatesh (2011) analysed selected material and energy flows in the water and wastewater system, and determined the environmental impacts associated with these flows for the system in Oslo. Venkatesh et al. (2009, 2012(a)) examined the stocks and flows of pipeline construction and rehabilitation materials and the energy consumption incurred during the operation and maintenance phase of the wastewater pipeline network and the water pipeline network, respectively in Oslo, for the period 1991 to 2006. The inflows of treatment chemicals into the water and wastewater treatment plants, and the demand for different energy carriers in the operation and maintenance phase of the entire system have been thoroughly discussed in Venkatesh et al. (2011(a), 2011(b), 2011(c) & 2012(b)). Using these studies as bedrock, the authors of this paper collaborated in the development of a 'Dynamic Metabolism Model' (DMM) for urban water services. The purpose has been to adopt a holistic systemic perspective to the analysis of metabolism and environmental impacts of resource flows in urban water and wastewater systems, in order to offer a tool for the examination of future strategies and intervention options in such systems. This model was subsequently tested for Oslo, and the results presented in the publication Venkatesh, Brattebø and Sveinung (2014). The WaterMet^2 model has also been tested for Oslo as a model city, and the results have been published recently. (Behzadian et al, 2014A & 2014B).

3. DESCRIPTION OF THE MODELS

DMM has been described in detail (supplemented with a user manual) in deliverable D34.1 (Venkatesh, Sægrov, Ugarelli and Brattebø, 2014), while the WaterMet^2 model has been described in D33.2 (Behzadian, Kapelan, Venkatesh, Brattebø, Sægrov, Rozos and Makropoulos, 2014). Readers are requested to access the said deliverables for detailed descriptions of the two models.

3.1. Dynamic Metabolism Model

Here, though, it would suffice to say that the DMM is a simple, flexible and modifiable, user-friendly MS-Excel-based model which accepts user-inputs in one single user-friendly file, uses inbuilt formulae, constants and 'intermediate' Excel files, and enables the end-user to test the impacts of changes expected planned/imagined in the future, on sustainability indicators defined under the categories: Social, Economic, Environmental, Functional and Physical (Refer Appendix I). The category 'Physical' represents 'Assets'. The dimension 'Governance' cannot be handled by this model. These indicators are on both per-capita basis and per-unit-volume-water supplied bases. As shown in Figure 1, the user populates the Excel files 'Notes and Assumptions' and 'User control' with information about the interventions and the assumptions made, and data, respectively. Calculations are done automatically to populate the series of files named 'Start year', Start year_plus_1' etc. These intermediate processed data are then used to automatically calculate and present the values of indicators in the file 'Final Results' in both tabular and graphical formats.

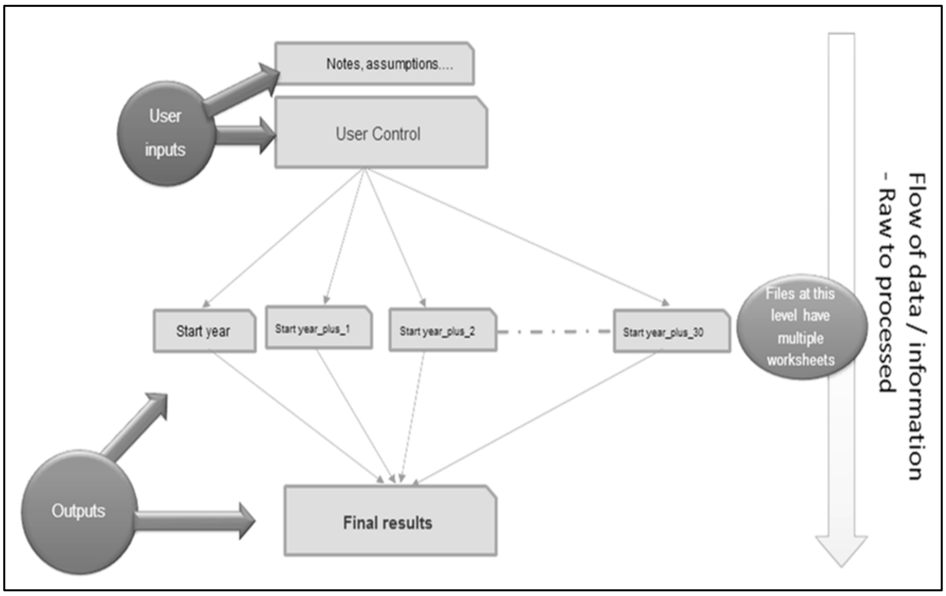

Figure 1: Structure of DMM and the flow of data and information through the model

3.2. WaterMet2 Model

WaterMet2 is a ‘conceptual, simulation type, mass-balance-based, integrated UWS model which quantifies metabolism-related key performance of UWS with focus on sustainability-related issues’ (Behzadian, et al, 2014A and 2014B). It is a standalone piece of software which runs in a Windows screen with the capability of navigational devices to build a new urban water system (UWS) model. It defines mains flows and storages of UWS through four main subsystems including water supply, water demand, wastewater and cyclic water recovery. Principal flows quantified by WM2 are all types of water flow, flux of energy (i.e. electricity, fossil fuel, embodied energy), greenhouse gas emissions (GHG), inter alia. The model recognises the UWS on four spatial scales - indoor, local, sub-catchment and city areas. A daily time step and a user defined period of N years are adopted as time interval and duration of model simulation in WM2. All this, in turn, will enable WM2 to model a wide range of elements in the UWS from residential appliances and fittings and water recycling schemes to simplified water supply and sewer systems. There are three more components which WM2 (current version) considers, which are not relevant for the case of Oslo (which is also the test-case for this paper), but can very well be so for other cities. These are ‘Subcatchment Rainwater harvesting’, ‘Subcatchment Greywater Recycling’, and Local Area Rainwater Harvesting and Greywater recycling’. The end-user can select from a maximum of 265 different KPIs (or rather categories of KPIs, as WM^2 labels them).

4. STATUS QUO IN OSLO’S WATER AND WASTEWATER SYSTEM AND INTERVENTIONS DEFINED

The status quo has been detailed in both the deliverables D34.1 and D33.2 in great detail. The scenarios and intervention-sets have been described in D34.1. (These deliverables have been referred to in the Literature Review section above). However, the interventions have been described here again, in sufficient detail. An additional intervention also figures in this deliverable, courtesy a request from Oslo VAV in May 2014 to test the same with the Dynamic Metabolism Model. Readers may kindly refer to the said deliverables for more information, if needed. Table 1 includes some of the main characteristics of the system.

Table 1: Characteristics of Oslo's water-sanitation system

MAIN RAW WATER RESOURCES	MARIDALSVANNET (90%), ELVÅGA (10%)
Water treatment plans	Oset WTP and Skullerud WTP
Length of water pipelines in network	1533 kilometres
Leakage from water pipelines	22% of total water supplied
Wastewater treatment plants	VEAS (63%) BEVAS (37%)
Length of wastewater pipelines in network	2253 kilometres
Population serviced (as on date)	Approximately 650,000

The interventions on the upstream (Venkatesh, Sægrov, Ugarelli and Brattebø, 2014) may include increasing water sources capacity and thus augmenting security of supply, increasing the water treatment plants' hydraulic capacity, improving the water treatment processes as far as water quality is concerned, improving distribution system performance, increasing consumer awareness, changing the water pricing system, reuse of water, and energy management. Those on the downstream, as tabulated in the same deliverable cited above, may include, inter alia, enhancing stormwater management, local solutions like grey water recycling, improving the transportation system performance (including combined sewer overflows), upgrading of the capacity and quality of wastewater treatment processes, energy and resource recovery and regional collaboration on wastewater management. These interventions are seen in the backdrop of risk factors – population increase and thereby a rise in demand for treated water, climate change which may affect the water resources, a rise in industrial demand for water, and deterioration in the assets (pipelines, pumps and treatment plants).

While strategizing for each of the risk factors (or sets of risk factors), the utility would ideally have to draw up concrete long-term plans regarding not just what interventions would be adopted, but also how they would be adopted. The greater the level of detail and accuracy in the data which can be provided to the DMM and WM^2, the more reliable and robust the outputs will be. Having said that, of course, the model can also perform 'what-if' analyses to aid the utility in understanding the best course of action (or combination of actions) to take.

In D34.1 and also in Venkatesh, Sægrov and Brattebø (2014), seven cases (discrete interventions and combinations thereof) were considered on the upstream side, and three on the downstream side. In D34.1, it was also pointed out why some of these cases could not be elaborately and systematically tested with WM^2. In this deliverable, an additional intervention on the upstream (rehabilitation of drinking water pipelines; and within this, a series of percentage rehabilitations) is considered. The discrete interventions (courtesy Oslo VAV, D34.1) which can also be read from D34.1 are anyway, listed again hereunder:

4.1. Upstream interventions

- Reduction in per-capita water demand (all demand excluding leakage) supplied by the water treatment plants from the current value, at a uniform rate of 1% per year, till 2040. The decreases are assumed to be wrought by a combination of measures ranging from awareness creation among consumers, construction companies in charge of new housing projects, and other market measures to promote the sales of water-saving equipment.
- Reduction in leakage from the network, at a rate of 1% per annum for the first 3 years of the time-period being studied. The leakage is expressed in terms of the percentage of the total water supplied by the WTPs into the distribution network, which itself may keep changing over time. Expenditure to the tune of 4.5 million NOK per year (in real currency units) are assumed to be incurred to bring this about. Hem (2013) of Oslo VAV noted that all the expenses would be directed to employing a team of 6 additional people. These expenses are added on in the model to the OPEX of the distribution network. Rehabilitating existing pipes is not included in this intervention, as pressure management is expected to accomplish the goals set (this however figures as a separate intervention).
- Installation of micro-turbines on the upstream to utilise the pressure head energy in the water flowing downhill to the water treatment plants. At a 50 metre head, utilizing approximately 22.5 million cubic metres to generate electrical energy, assuming a turbine efficiency of 90%, a yield of 2.75 GWh is obtained. This is sold to the electricity grid at the same tariff rate at which electricity is purchased from it by the utility. The investments required to set up the turbines are assumed to be to the tune of 2 million NOK, committed in year-2018; and are added on to the capital

investments into the water treatment plants, in the model. The O&M expenses that may be incurred in maintaining the turbines are neglected.

- The raw water is sourced from Holsfjorden – a source located to the west of the city, necessitating the setting up of a facility close to it, and associated piping and pumping. Data for the capital investments required for this purpose, are sourced from Paus & Hem (2012). Holsfjorden in this case provides 20% of the raw water, with the lake Maridalsvannet (in the north) providing 67.9% and the lake Elvåga (in the east), 12.1%.

In addition to the first four discrete interventions, combinations 'a+b+c', 'a+b' and 'a+b+d' were also considered in D34.1.

4.2. Downstream interventions

In keeping with the designation of the interventions, the list begins with (e).

- *Upgrading and changes to the wastewater transport system* - The rehabilitation rate of wastewater pipelines which is 1.3% in year-2013, rises to 1.6% in year-2016 and stays at that level till year-2040. The stream of investments committed to rehabilitation is considered (VAV, 2013). In the absence of detailed information about the lengths and diameters of pipelines likely to be rehabilitated, the shares of large, medium and small in the mix, are considered to be the same as in 2013. The lengths of all the three increase by a factor of (1.6/1.3), this being the ratio of the new rehabilitation rate to the current one. Also, the annual investments committed to rehabilitation of wastewater pipelines by Oslo VAV, as per the Master Plan – VAV (2013), are to the tune of 174 million NOK (approximately 21.8 million Euros). This is assumed to hold from 2016 till the end of the study period. The capital investments made are depreciated linearly over 40 years. Interest payments made are also assumed to increase in tandem with the annual depreciation.

- *Upgrading and investments at BEVAS WWTP:* The treatment capacity at Bekkelaget wastewater treatment plant (BEVAS) rises from 290,000 PE (person-equivalent) now to 490,000 PE in 2019. It stays there for the remainder of the study period. Also, as the amount of wastewater treated at BEVAS increases, the biogas produced also rises. The demand for refined biogas in the transport sector is slated to increase over time. The cost of in-plant transport fuel production (real Euros per kWh), varies over time and gradually tapers to a constant, and is based on background data used for a book chapter (Elmi and Venkatesh, 2014). Investment in upgrading of BEVAS accounts for a large portion of investments committed to wastewater treatment. Hence, this is the only one which has been considered here. For the expansion of BEVAS from 2014 to 2019, the investment streams in million NOK are 100, 360, 430, 450, 600 and 820 million NOK (VAV, 2013). These investments are depreciated linearly over 30 years. The shares of biogas used for electricity generation, heat production and transport fuel generation, are assumed to increase in proportion to the biogas captured and utilised in the plants (VEAS and BEVAS).

The combination 'e+f' was also considered in D34.1. This of course is the most likely as the utility would ideally improve both transport and treatment. In addition to the discrete interventions and combinations on the upstream and downstream, two grand combinations 'a+b+d+e+f' and 'a+b+c+e+f', are also tested. These two, needless to say, would incur more expenses (capital and O&M) and also result in greater benefits.

A new upstream intervention – let us call it 'g' – was added on, after the deliverable D34.1 submitted: "*Rehabilitating drinking water pipelines – different annual rates of rehabilitation tested (1%, 1.25%, 1.5%, 2%, 2.25% and 2.5%)".* This was the consequence of a meeting NTNU had with Oslo VAV personnel to discuss the deliverable D34.1 and possible further work with one or both the models. Also to be mentioned quite clearly here is the fact that it was easier to test the rehabilitation interventions using DMM (at NTNU's end); and the results presented for this intervention 'g' are outputs from the DMM.

5. RESULTS AND DISCUSSIONS

In D34.1, results obtained from the two models have been presented. In other words, the performance analysis for Oslo as a case city, actually dwelt on the status in year-2040, for the different interventions and intervention-combinations referred to above. The authors thereby would refrain from repeating the same, in toto, here. However, for the sake of recapitulation, in this deliverable, some results are presented and described in detail. Let us consider GHG emissions, for that figures prominently on the radars of many governments and utilities these days. In this context, let us start off with this premise:

"*A reduction in GHG emissions can be brought about by changes in operational and maintenance procedures and/or process improvements. Some capital investments may also be called for. However, capital investments into the system, it must be borne in mind, provide several benefits one of which may be the reduction of GHG emissions. Hence, a direct correlation between all capital investments (annual capital expenses serving as a proxy for this) into the system and a reduction of GHG emissions per capita does not exist. In fact, some capital investment streams may themselves entail resource consumption and consequent GHG emissions (upstream or on-site)".*

Consider Figures 2 and 3. Capital investments committed to rehabilitating the wastewater pipeline network ('e') – a steady annual stream till 2040 – acting alone, raise the value of this indicator above that in 2013. At the same time, when the lumped capital investments committed into the system in 'f' act alone (the white square in Figure 18), the value drops below 1, in year-2040. When all three happen in tandem (in the combination 'a+b+d+e+f'), the effect is conspicuous in Figure 3.

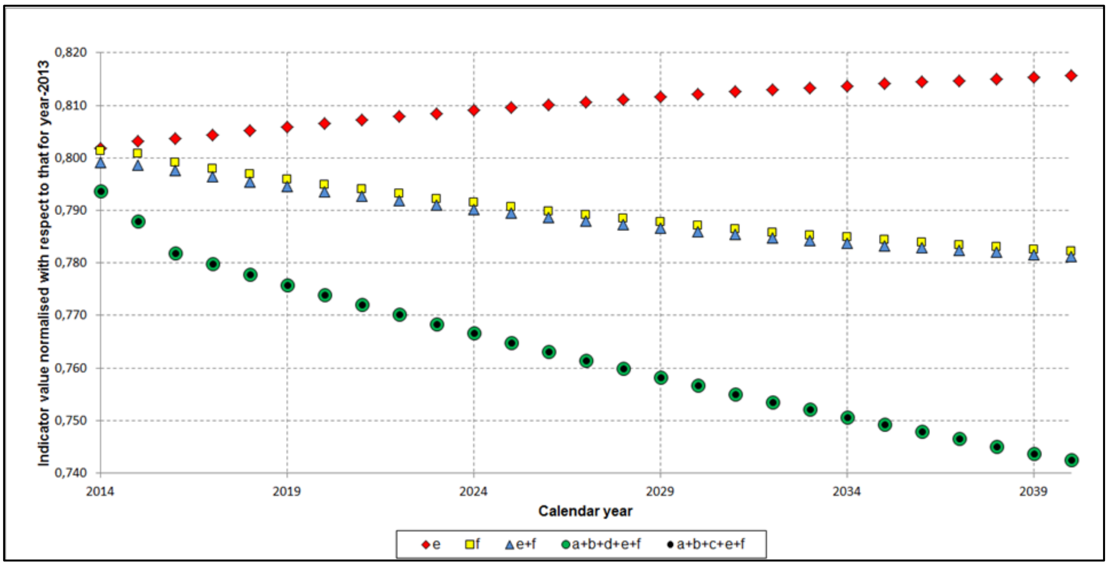

Figure 2: Change in GHG emissions per capita ('e', 'f', 'e+f', 'a+b+c+e+f' and 'a+b+d+e+f')

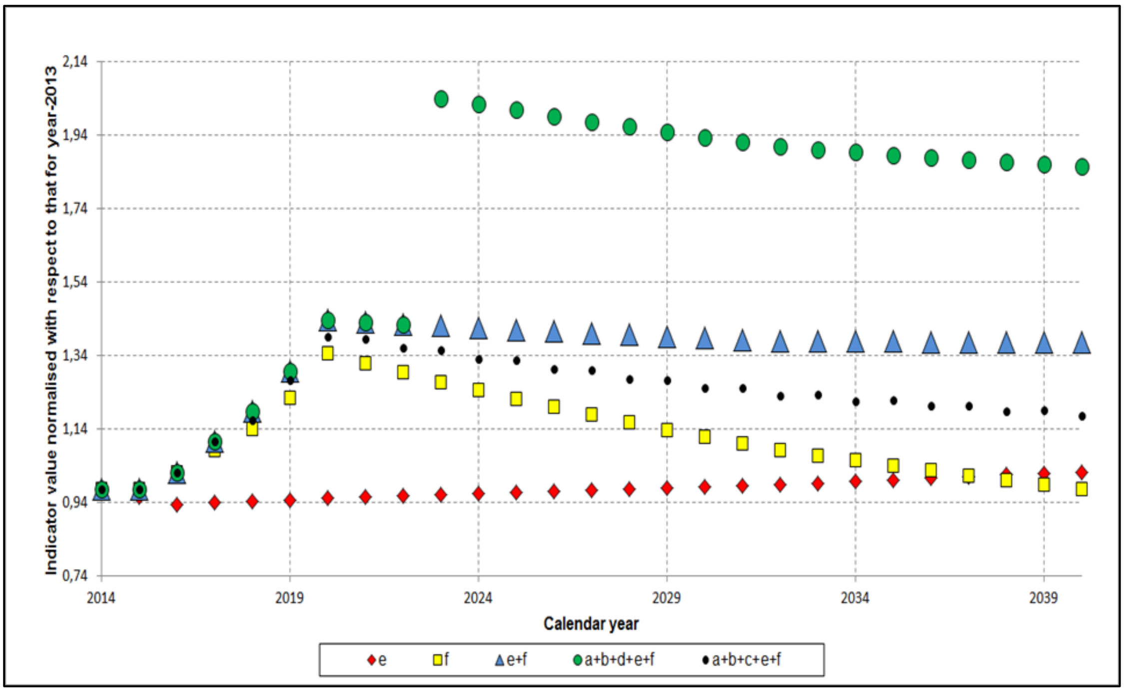

Figure 3: Change in Capital expenditure per capita ('e', 'f', 'e+f', 'a+b+c+e+f' and 'a+b+d+e+f')

It is seen that the greatest reduction in specific GHG emissions occurs in the two grand upstream-downstream combinations – 'a+b+c+e+f' and 'a+b+d+e+f' (Figure 2). Note that the trends for both these combinations are exactly the same and they overlap each other in Figure 2. This is quite intuitive. However, the specific capital expenses in the case of the former are much lower than that in the case of the latter. If the purpose is simply to bring down the specific GHG emissions as much as possible, then the utility would opt for the combination 'a+b+c+e+f'. However, decision-making is not usually as simple as that. The objectives are usually many. In this case, bringing a new water resource on-stream is vital to fulfil the objective of providing water to a growing population. Thus, the additional capital investments committed for this purpose are not only advisable but mandatory from the point of view of providing a necessary service to the inhabitants of the city. Likewise, expanding the capacity of the WWTP at BEVAS is also imperative, considering that an increase in water demand on the upstream results in an increase in the wastewater volumes that need to be handled on the downstream. The exercise carried out in this report does not tell the utility *per se* which intervention or set of interventions to select, but rather demonstrates how the values of indicators would change for different interventions or sets of interventions. Some of these interventions will anyway have to be carried out, as governmental regulations would deem them to be mandatory.

Now, let us move on to the WaterMet^2 model and the tests and results therewith and thereof, in D34.1. As mentioned in the previous deliverable, interventions are defined in WM2 through the Decision-Support System, and this would mean that we are talking of an evolution over time. In the DMM, on the other hand, an intervention defined in clear times, can be at once incorporated and tested. Once again, it must be mentioned, in order to avoid any misunderstanding, that this is just a difference between the two models, as they stand on-date, and not necessarily a benefit or advantage of one over the other. Working with the model as it is, in D34.1, 'a', 'b', 'c', 'd' and 'f' were tested first, followed by a grand combination – 'a', 'b', 'c' and 'f'. It must be repeated here that 'e' was not modelled. This, as referred to earlier in the paragraph is an intervention which has to be defined in the model first, to be tested. The unique feature of WM2 is the plethora of indicators which can be obtained by making suitable selections. It has over 250 categories of KPIs, for each of these interventions (or combination of interventions). As in D34.1, it would not be possible to dwell on all these in great detail. Hence, some sample outputs are presented hereunder for selected indicators for selected interventions. Just for the sake of variety, we have not considered the same indicators as for DMM. Apart from variety, another key reason is the fact that the WM2 is more of a conceptually-based model onto which the metabolic and environmental aspects have been pinned.

Figure 4, for instance, plots on a daily basis for the period up to year-2040, a prognosis of the fraction of water demand delivered. Climate change (less precipitation and warmer summers requiring more water for garden-watering, for instance), population growth, water usage patterns etc., influence the trend depicted hereunder. If the objective of the utility is to always be able to meet the water demand 100%, and if it is evident that simply adding on a new water resource is not going to solve the problem of not being able to do so, it could consider adding on other interventions – increasing consumer awareness and/or reducing leakages by pressure management, rehabilitation etc., and thus reducing water demand, installing water meters and expanding capacities wherever possible, and so on. Thus, Figure 4 would be instructive as far as the limits of intervention 'd' are concerned, *ceteris paribus.* Note that WM2 can provide the information illustrated by Figure 4, in different time resolutions – weekly, monthly and annual.

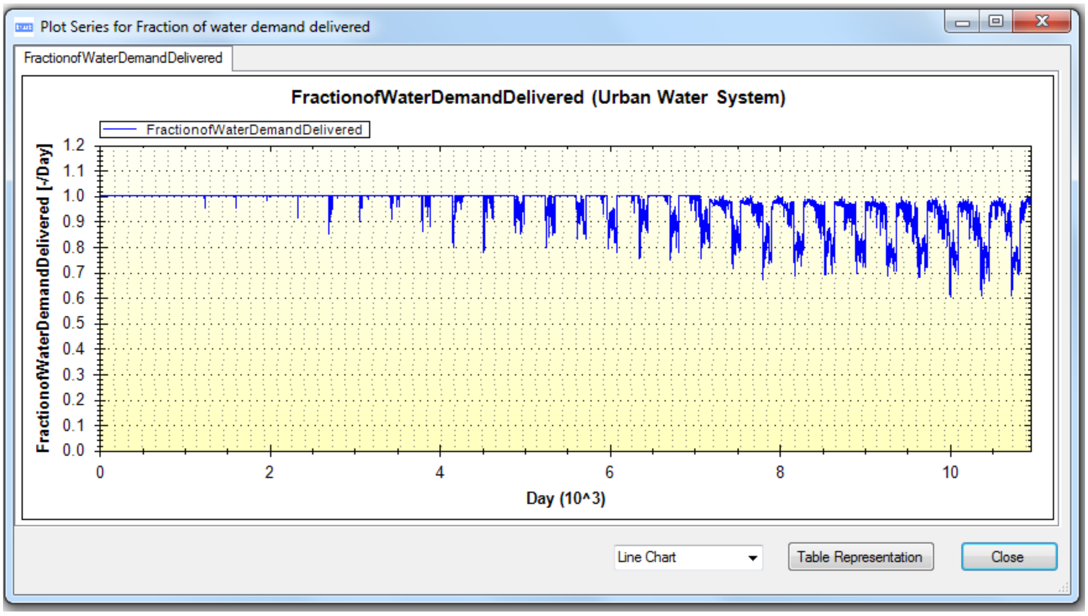

Figure 4: Fraction of water demand fulfilled in Oslo, under Intervention 'd' (a prognosis)

Figure 5 depicts the GHG emissions – categorised by colour-coding into total, electricity-based, fossil-fuel-based, and embodied (in materials and chemicals consumed) – in the entire water-wastewater system in Oslo. Electricity is needed to treat raw water and wastewater, and to pump the same, while chemicals (the main reason for embodied energy demand) are consumed in water and wastewater treatment. In Oslo, fossil fuel consumption is associated with diesel use in standby generators in one of the water treatment plants, and in the pipeline network rehabilitation and maintenance phases. The spikes coincide with the spring and summer months in Oslo, when water demand (largely driven by garden-watering needs) rises. It is also in spring that snow melts and the loading on the wastewater treatment plants is higher. Also, over the 24 hours which make up a single day, the water demand varies (peaking in morning and evening; and dropping in the afternoon and at night), and consequently the resource usage, and the associated GHG emissions.

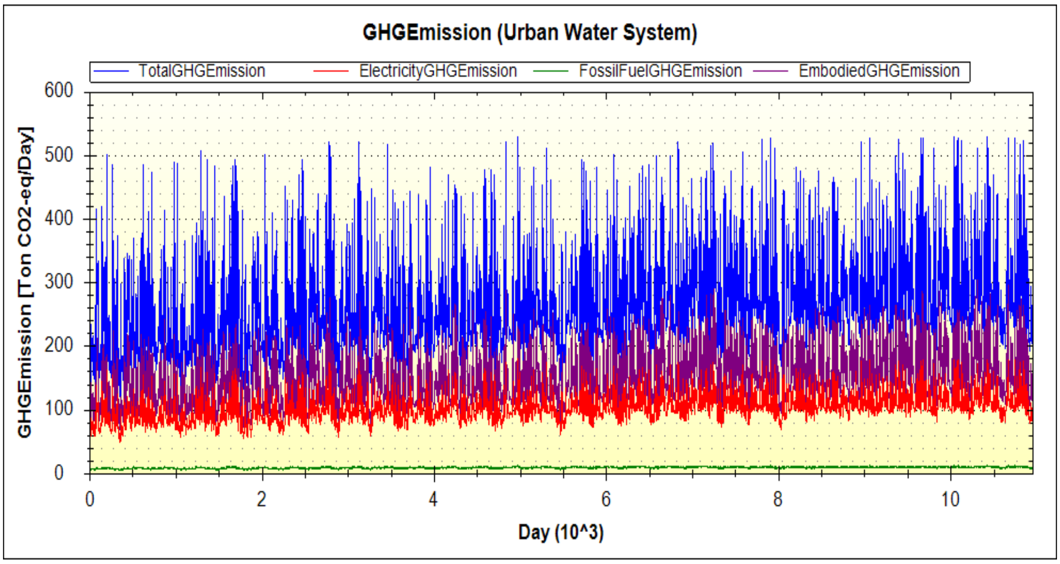

Figure 5: GHG emissions in the entire water-wastewater system in Oslo, under Intervention 'd' (a prognosis)

It must be mentioned that the GHG emissions have not been modelled comprehensively in WM^2 (for instance, the utilisation and environmental impacts (caused and avoided) of biogas in WWTWs). This would be one of the reasons why there would be variations in the results for GHG emissions between DMM and WM2. However, having said that, it can be mentioned that this can be incorporated into WM2 at a later stage, as it continues to evolve. This report may not be able to truly represent all the capabilities of the current version of WM2. Suffice to say that the range of KPIs needs to be explored by the end-user/reader, by working with the model interactively, and understanding the plethora of possibilities it provides for sub-systemic and systemic analysis and decision-making.

These results were also presented in D34.1. After D34.1 was submitted, as referred to above, the intervention 'g' was tested using DMM alone. Appendix II summarizes the data and assumptions related to this test. A snapshot of the results of this test is presented hereunder. Figures 6 and 7 are self-explanatory and provide a very clear picture of the effect of rehabilitation on the water demand per capita and the capital expenditure per cubic metre water demand, in the water distribution system. It should be noted here that this test narrows down the scope and focuses on the effect of different rehabilitation rates on indicators pertaining to only the water distribution system. The effect on the pan-systemic indicators can also be easily demonstrated using the DMM. Those results however have not been presented in this deliverable (they could be made available to those interested, on request).

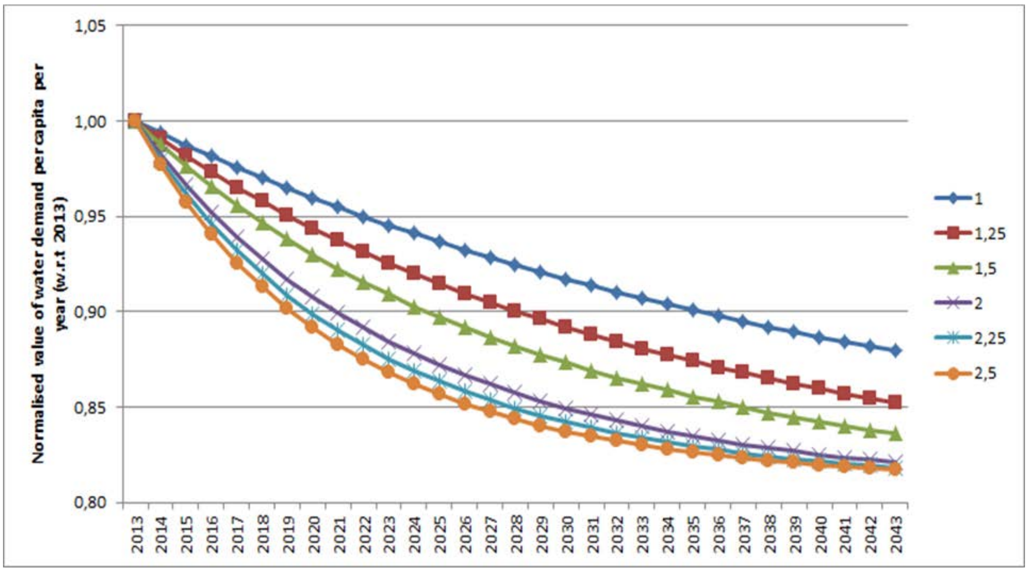

Figure 6: Intervention 'g' - Effect of degrees of rehabilitation on the water demand per capita per year, in the water distribution system (Each line represents one particular annual rehabilitation percentage).

It is year-2040 which is of concern here, even though in Figures 6 and 7, the maxima on the X-axis is year-2043. The drop in the value of the indicator (from 2013 to 2040) – water demand per capita per year - is in the range of 12% to 18% (1% rehabilitation to 2.5% rehabilitation). However, from Figure 7, it is evident that the effect of rehabilitation on the value of the indicator – annual capital expenses per cubic metre water demand – is more conspicuous. It ranges from a 3% drop for a 2.5% rehabilitation rate to over 20% for a rehab-rate of 1%. The fact that water demand is restrained by increasing the rehabilitation rate (thereby pulling back the rate of increase in the denominator of the indicator), plays a role here.

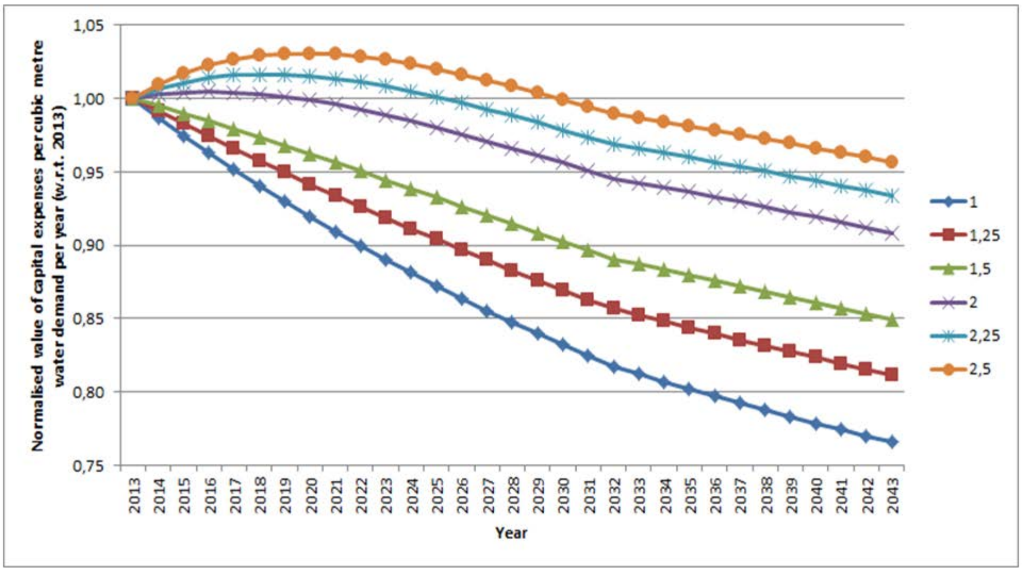

Figure 7: Effect of degrees of rehabilitation on the annual capital expenditure per cubic metre water demand in the water distribution system (Each line represents one particular annual rehabilitation percentage)

Table 2: Relative values in year-2040 for selected systemic indicators to demonstrate the effect of rehabilitation and consequent leakage reduction in water pipelines (normalized with respect to 2013)

INDICATOR FOR THE WHOLE SYSTEM	REHABILITATION RATE IN %					
	1%	1.25%	1.5%	2%	2.25%	2.5%
GHG emissions per capita (CO2e kg)	0.944	0.928	0.918	0.908	0.905	0.904
Total energy consumption per capita (kWh)	0.86	0.833	0.817	0.801	0.798	0.796
GHG emissions per cubic metre demand (CO_{2e} kg)	1.073	1.088	1.097	1.105	1.105	1.105
Total treatment chemicals per capita (kg)	0.822	0.8	0.787	0.775	0.773	0.772

In Table 2, the effect of leakage reduction by rehabilitation on the use of treatment chemicals in the upstream and downstream of the system becomes evident. A rise in the rehabilitation rate from 1% to 2.5%, has a conspicuous impact on the relative value of this indicator in year-2040 – it falls from 0.822 to 0.772.

The value of the first indicator in Table 2 drops over the time-period, while that of the third tends to rise gradually (by 7% for a 1% rehabilitation rate, and 10% for rates above 2%). The curves for 2%, 2.25% and 2.5% tend to merge towards the right of the graph. A little thought experiment will reveal that rehabilitation and replacement which consumes diesel, polyethylene and polyurethane (all of which result in GHG emissions upstream), tend to hold back the rate of rise in the volumes of water demand. However, as the total water volume still increases (as the population increases), the associated GHG emissions attributed to treatment and pumping increase. There is also a conspicuous addition in the form of GHG emissions attributable to the consumption of diesel, polyethylene and polyurethane. Quite like the specific consumption of treatment chemicals (with respect to the population), the relative value of the total energy consumed in the entire system per capita in year-2040 drops with a rise in the rehabilitation rate (0.86 for 1% to 0.796 for 2.5%).

Again, it will not be possible to say what is the optimum rehabilitation rate to be pursued, unless one knows what are the indicators of relevance the utility wishes to work with and how they rank/weight these. It is a matter here of considering indicators of different types – functional (rehabilitation rate, leakage rate), environmental (GHG emissions, acidification etc., on a per-capita basis), physical (possibly pipeline material mass per capita, if lightening the network in this regard could be an objective) and economic (capital costs and O&M expenses expressed as appropriate indicators).

With regard to all the results presented above, it needs to be emphasized that if the utility has specific targets / benchmarks for a host of indicators, then the impact of different interventions or sets of interventions (which may necessarily have to be carried out), can be analysed, vis-à-vis these targets. However, just having targets will not be enough. The different objectives may need to be prioritized or weighted, in order to arrive at an optimum solution (or set of solutions), based on distance from the targets set for each of the indicators. Top-priority concerns (generally from a politico-legal perspective) will inevitably trump the others during the decision-making process. In a simplified case, as in case of say Figure 2 and Figure 3, one would have to contend with just two metrics – costs and GHG emissions. However, generally speaking, utilities would first have to assign weights to the criteria and within each of the criteria, sub-weights to the indicators of interest. For instance, if the environmental criteria is given a weight of 30% (vis-à-vis the others), the utility may have one or more indicators of concern under this criterion. If there is only one, say, GHG emissions, it would take a weightage of 30%, vis-à-vis all the indicators considered under all the metrics. If there are two, say GHG emissions, and Acidification, the utility would need to sub-weight these two, so that the 30% weightage assigned to the environmental criteria is suitably apportioned.

The PLAN method which is being developed as part of the Decision Support System in TRUST offers the possibility to perform the trade-offs among different interventions, including the use of weighting. However, this is beyond the scope of this particular report. If this had to be done, one would have needed the input of specific target values and threshold values from Oslo VAV, which have not been provided to the authors by the utility. While this unfortunately cannot be tried out for this very reason now, utilities would need to be trained to think on these lines, in order to benefit optimally from the use of these models. The importance or rather the indispensability of weighting and prioritising has been communicated to the Oslo VAV personnel; and quite understandably, there is an initial reluctance to do so, which hopefully will be overcome with time.

6. COMPARISONS

The DMM and WM2 are totally different models, for that matter. While the DMM is a simple, user-friendly, flexible Excel-based model, with limited capabilities, WM2 is a more sophisticated, software-based model with a slightly wider range of capabilities. However, neither of these two is a silver-bullet solution to all the data-management and decision-making challenges faced by utilities. Different utilities, at different points in time, for different purposes, would possibly find either of the two useful. Table 2 briefly summarises the characteristics of these two models, by referring to the points of differences.

Table 3: Points of difference between DMM and WM2 (tabulation of text in D34.1)

	DYNAMIC METABOLISM MODEL	WM2 MODEL
Basic structure	MS-Excel based (industrial-ecology inspired)	Software code-based (Conceptual and metabolism-based)
Biogas generation, capture and use	Modelled in detail (the avoided environmental impacts as well)	Modelled in detail (the avoided environmental impacts as well)
Capital costs	Modelled as a sum of depreciation and annual interest payments	Not done in this fashion. Capital investments of new intervention options need to be calculated out of WM2
Climate change effects	Not modelled	Modelled using time-series a weather data.
Describing interventions	Interventions can be directly incorporated into the Excel file/s	Interventions are defined in through DSS out of WM2 and WM2 will support a set of intervention options.
Indicators	Expressed in per-unit-volume-water-supplied and per-capita terms, as required.	Expressed in absolute amount per unit of time (i.e. day, week, month, year, planning horizon).
Modifiability	Easily modifiable by anyone who is familiar with Excel	If there are major changes called for, some changes to the background software code may be called for, though not necessarily
Primarily defined as	Metabolism-based, or mass-balance-based	Metabolism-based, or mass-balance-based
Spatial aspects	City-scale analysis only in the present version	Four scales of city, sub-catchment, local area, household
Temporal aspects	Annual trends	Daily time step for a duration of long-term planning horizon

Having pointed out the differences between the two models, it must be mentioned at this juncture that the purpose is clearly not to present one over the other as an all-weather model which utilities should adopt in their decision-making. The basic premises on which these models were developed – WM2 on a conceptually-based and metabolism one with possibilities for high temporal and special resolution, and DMM on a metabolism one with the possibility of simpler analysis of annual or seasonal data, contribute to the difference in their structure and the nature of the outputs obtained from them. For a general 'systemic' overview, on a year-to-year basis, which strategic managers could benefit from, and apply to decisions at the strategic level, the DMM, with its systemic outlook is suitable (recognition phase). If tactical and operational decisions on a quotidian basis are to be taken, and utilities seek a tool to guide them onward, the WM2 is apt although WM2 is not the final step. More specifically, for further analysis of the strategic-level planning of the future UWS for new intervention options (feasibility study) in which the level of detail modelled may not be able to provide the detailed list of interventions to be implemented, a WM2 model would be suitable. However, the DMM model 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 (design phase). Hence, the next phase of WM2 modelling would need to use more sophisticated models of specifically selected intervention options. Thus, one model complements the other. Further work would be needed, resulting in a likely sequel to this report. As Oslo is the model city which has been considered in this report, the authors intend to interact with the officials at Oslo VAV in the time to come, discuss more closely the usefulness / suitability of both models to problem-solving and decision-making, and seek their inputs and viewpoints, in the ongoing process to provide the utility with a relatively flexible toolkit to use, to find solutions to different kinds of problems, answers to questions of varying nature.

Also to be repeated here is the fact that DMM and WM2 provides a host of indicators, some of which are valid and useful inputs to the Decision-Support-System. Those which are beyond the scope of the indicator-list propounded by IWA, may be availed of by utilities which would need to tailor-make the decision-making process to their own specific contexts, needs and goals. The DSS needs to avail of other sources of input for indicators and metrics which the DMM and WM2 cannot provide. In other words, the sources of data for the Decision-Support-System would thus be varied, with DMM and WM2 being two of them.

7. FEEDBACK AND GLEANINGS FROM UTILITIES

The authors solicited feedback from the Oslo water and wastewater utility about their experiences with using and opinions about the two models. Lars Hem and Jadranka Milina from Oslo VAV tell the authors *(in an e-mail correspondence received by G Venkatesh, on the 6th of August 2014)* that both the DMM and WM2 models were used to evaluate the sustainability for various alternative strategies for water supply in the city in the future. According to them, the development of a metabolism model for the entire urban water/sanitation system using real data is a complex task involving efficient teamwork on the methodological approach, data acquisition and the verification of the model. Such models, invariably require considerable volumes of data; and the quality of the output depends on the quality of the input (which includes cost estimates for the alternative strategies one would like to test). In their opinion and rightly so, the use of cost estimates calculated from different sources or countries are likely to give erroneous results. They also stress on the fact that the quality of the output certainly would depend on trust, good communication and understanding between utilities and researchers/analysts. Hem and Milina believe that the WM2 model requires more data than the DMM model; and the latter was found to be relatively simpler and more transparent.

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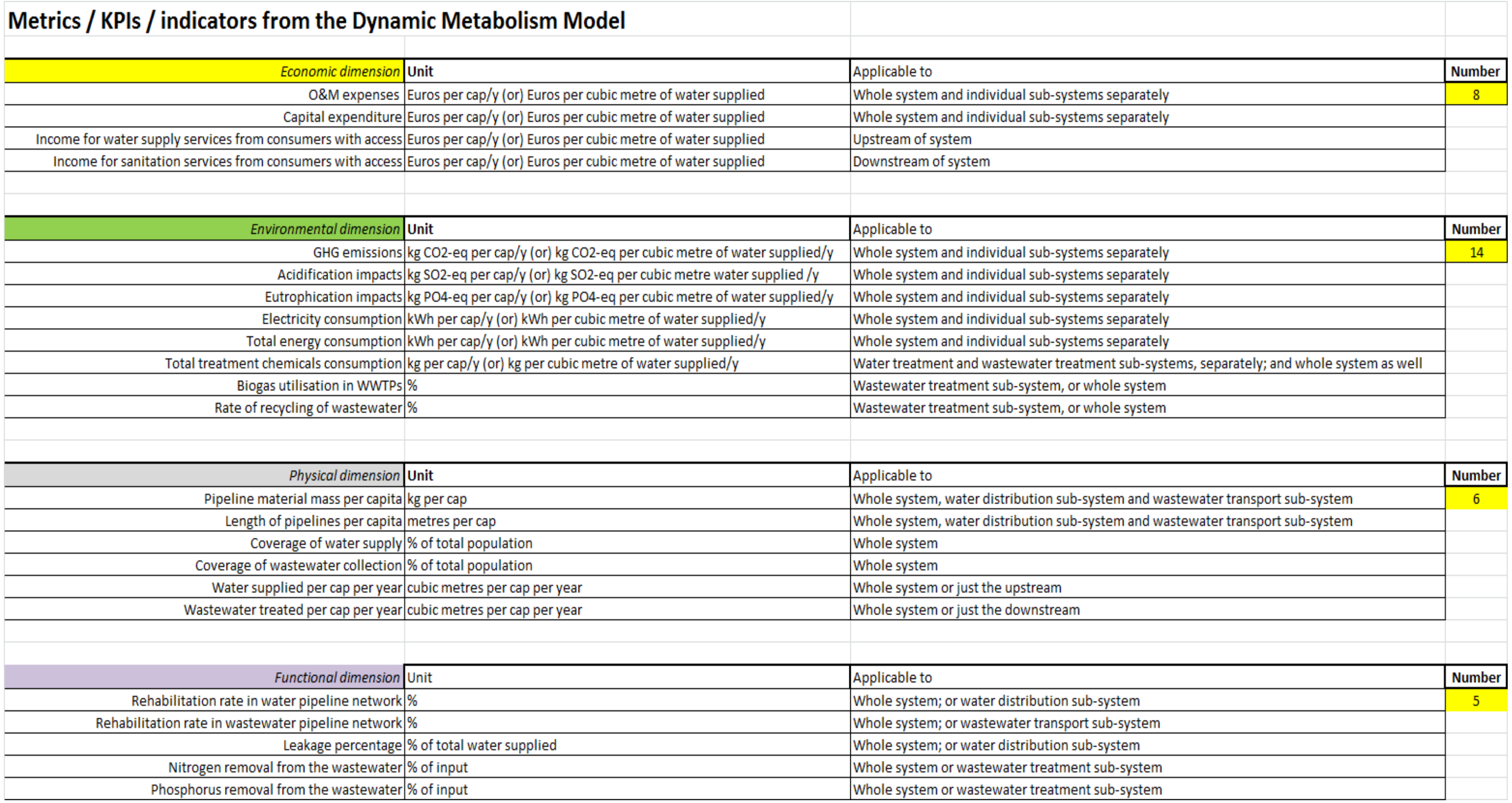
APPENDIX (I)



Metrics / KPIs / indicators from the Dynamic Metabolism Model

Economic dimension	Unit	Applicable to	Number
O&M expenses	Euros per cap/y (or) Euros per cubic metre of water supplied	Whole system and individual sub-systems separately	8
Capital expenditure	Euros per cap/y (or) Euros per cubic metre of water supplied	Whole system and individual sub-systems separately	
Income for water supply services from consumers with access	Euros per cap/y (or) Euros per cubic metre of water supplied	Upstream of system	
Income for sanitation services from consumers with access	Euros per cap/y (or) Euros per cubic metre of water supplied	Downstream of system	

Environmental dimension	Unit	Applicable to	Number
GHG emissions	kg CO2-eq per cap/y (or) kg CO2-eq per cubic metre of water supplied/y	Whole system and individual sub-systems separately	14
Acidification impacts	kg SO2-eq per cap/y (or) kg SO2-eq per cubic metre water supplied /y	Whole system and individual sub-systems separately	
Eutrophication impacts	kg PO4-eq per cap/y (or) kg PO4-eq per cubic metre of water supplied/y	Whole system and individual sub-systems separately	
Electricity consumption	kWh per cap/y (or) kWh per cubic metre of water supplied/y	Whole system and individual sub-systems separately	
Total energy consumption	kWh per cap/y (or) kWh per cubic metre of water supplied/y	Whole system and individual sub-systems separately	
Total treatment chemicals consumption	kg per cap/y (or) kg per cubic metre of water supplied/y	Water treatment and wastewater treatment sub-systems, separately; and whole system as well	
Biogas utilisation in WWTPs	%	Wastewater treatment sub-system, or whole system	
Rate of recycling of wastewater	%	Wastewater treatment sub-system, or whole system	

Physical dimension	Unit	Applicable to	Number
Pipeline material mass per capita	kg per cap	Whole system, water distribution sub-system and wastewater transport sub-system	6
Length of pipelines per capita	metres per cap	Whole system, water distribution sub-system and wastewater transport sub-system	
Coverage of water supply	% of total population	Whole system	
Coverage of wastewater collection	% of total population	Whole system	
Water supplied per cap per year	cubic metres per cap per year	Whole system or just the upstream	
Wastewater treated per cap per year	cubic metres per cap per year	Whole system or just the downstream	

Functional dimension	Unit	Applicable to	Number
Rehabilitation rate in water pipeline network	%	Whole system; or water distribution sub-system	5
Rehabilitation rate in wastewater pipeline network	%	Whole system; or wastewater transport sub-system	
Leakage percentage	% of total water supplied	Whole system; or water distribution sub-system	
Nitrogen removal from the wastewater	% of input	Whole system or wastewater treatment sub-system	
Phosphorus removal from the wastewater	% of input	Whole system or wastewater treatment sub-system	

APPENDIX (II)

References useful for the test of intervention ‘g’

1. Egeplast (2013). Egeplast price list for polyethylene plastic pipe systems. Downloaded from the Internet - http://www.egeplast.de/wp-content/uploads/2013/06/egeplast-price-list-for-plastic-pipes-2013.pdf - on 23rd May 2014.
2. PRé Consultants. Simapro 7.1.5. Amersfoort, the Netherlands: PRé Consultants, 2008.
3. Swiss Centre for Life-cycle Inventories. Ecoinvent database v 2.01. www.ecoinvent.org.
4. Ugarelli, R., G Venkatesh, Helge Brattebø & Sveinung Sægrov. 2008. Importance of investment decisions and rehabilitation approaches in an ageing wastewater pipeline network. A case study of Oslo (Norway). *Water Science and Technology*, 58.12, Pages 2279-2293.
5. http://www.robnor.co.uk/ - Robnor Resins, United Kingdom.
6. http://www.business.com/guides/pricing-and-costs-of-polyurethane-foam-24935/. Accessed on 23 May 2014, for the price of flexible liquid PU foam.

Relationship between rehabilitation and leakage (and leakage reduction)

E-mail correspondence with Lars Hem, Oslo VAV, 14th May 2014:

‘’The number itself (0.5 %) is more or less out of the blue, but the points are:

- with no rehab the leakage is assumed to increase
- more rehab means faster decrease in leakage

As I also suggested, after some time the *-d(leakage)* will be reduced to 0.8*(Rehab-0.5) or 0.8*Rehab-0.5, and after that further reduced, since the effect will be most pronounced in the beginning when we (hopefully) rehabilitate the worst pipes and areas.

Most likely, the d(leakage) should be a function of the total leakage, so the 0.8 may be exchanged by a more complex function like 5*(total leakage as fraction).

This obviously is a **highly empirical and logic approach**, not a scientific one. It is unlikely that we ever get down to 0% leakage.’

On the basis of this e-mail correspondence, the relationship between (annual) reduction in leakage and rehabilitation rate is considered to be the following:

$$-\Delta leakage\ (\%) = 5 \times (Total\ leakage\ as\ fraction) \times (Rehab\% - 0.5)$$

Other useful data for the analysis

- Diesel use in installation (replacement) and rehabilitation

DESCRIPTION	VALUE (IN l/m OF PIPE)
INSTALLATION OR REPLACEMENT	
Large-diameter (400 mm and greater)	35
Medium-dia (200 mm to 399 mm); (Average of 300 mm; outer dia. - PE pipes)	30
Small-dia. (199 mm and less); (Average of 100 mm; outer diameter for PE pipes)	25
REHABILITATION	
Large-dia. (400 mm and greater)	2
Medium-dia. (200 mm to 399 mm); (Average of 300 mm; outer dia. for PE pipes)	1.5
Small-dia. (199 mm and less); (Average of 100 mm; outer dia. for PE pipes)	1

- Specific gravities of plastics (Venkatesh, 2011)
  - Polyethylene : 0.93
  - Polyurethane : 1.05
  - Polyurethane coating during CIPP : 2-4 mm
  - Diameter to thickness ratio of PE: 11
- Price of PE pipes (Egeplast, 2013)
  - 100 mm diameter PE pipe : 29 Euros per metre
  - 300 mm diameter PE pipe : 297 Euros per metre
- Price of flexible liquid PU foam used for CIPP (http://www.business.com/guides/pricing-and-costs-of-polyurethane-foam-24935/. Accessed on 23 May 2014): 30 USD for 53 ounces. 14 Euros for 1 kg.
- Specific gravities of: (Venkatesh, 2011)

  - Ductile iron : 7.1
  - Grey cast iron: 7.1
- Thickness of grey cast iron and ductile iron pipes (Venkatesh, 2011)
  - Grey cast iron: 100 mm dia (9 mm); 300 mm dia (13 mm)
  - Ductile iron : 100 mm dia (100 mm dia (6 mm); 300 mm dia (7.2 mm)

REFERENCES

Behzadian, K., Kapelan, Z., Venkatesh, G., Brattebø, H., Sægrov, S., Rozos, E. and Makropoulos, C. (2014). Quantitative UWCS performance model. Deliverable to TRUST, D33.2.

Behzadian, K., Z. Kapelan, G. Venkatesh, H. Brattebø and S. Sægrov. WaterMet2: a tool for integrated analysis of sustainability-based performance of urban water systems. Drink. Water Eng. Sci. Discuss., 7, 1-26, 2014B

Behzadian, K; Kapelan, Zoran; G.Venkatesh; Brattebø, Helge; Sægrov, Sveinung; Rozos, Evangelos; Makropoulos, Christos; Ugarelli, Rita Maria; Milina, Jadranka; Hem, Lars J.. Urban water system metabolism assessment using WaterMet2 model. Procedia Engineering 2014A; 70:113-122.

Brattebø, H., Bergsdal, H., Sandberg, N., Hammervold, J., Müller, D., 2009. Exploring built environment stock metabolism and sustainability using systems analysis approaches. Building Research and Information 37(5), 569-582.

Brattebø, H., Sægrov, S., and G Venkatesh (2011). "Metabolism modelling of urban water cycle systems - System definition and scoping report", TRUST, Internal deliverable, WA 3.3.

Brunner, P.H., Rechberger, H., 2004. Practical handbook of material flow analysis. Lewis Publishers. New York. USA. ISBN 1-5667-0604-1.

Hem, L. Oslo Water and Wastewater Authority, Oslo, Norway. Personal communication in Trondheim, 2013.

Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environmental Pollution 159 (8-9), 1965-1973.

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

Makropoulos, C.K., Natsis, K., Liu, S., Mittas, K., Butler, D., 2008. Decision support for sustainable option selection in integrated urban water management. Environmental Modelling & Software 23(12) 1448-1460.

Paus. R and Hem. L (2012). KVU Vannforsyning Oslo – Innfasing av ny vannkilde. For NorConsult. SINTEF. NIVA. dated 30-5-2012

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

VAV, 2011a. 'Forecast of Water Usage in the Future in Oslo' translated from the original Norwegian version to English by G Venkatesh 'Water Treatment Plant Bulletin' by Oslo Water. Oslo Water and Sewerage Works: Oslo, Norway.

VAV, 2011b. 'Rough Analysis of Alternatives' translated from the original Norwegian version to English by G Venkatesh 'Water Treatment Plant Bulletin' by Oslo Water. Oslo Water and Sewerage Works: Oslo, Norway.

VAV, 2013. Hovedplan - Avløp og Vannmiljø (Masterplan - Sewage and the hydrosphere). 11 December 2013.

Venkatesh G and Helge Brattebø (2014) Studying the demand-side vis-à-vis the supply-side of urban water systems –Case study of Oslo, Norway. Environmental Technology. 35(18): 2322-2333.

Venkatesh G., Helge Brattebø and Sveinung Sægrov (2014). Dynamic metabolism modeling of urban water services - demonstrating effectiveness as a decision-support tool for Oslo, Norway. Water Research, Vol 61: 19-33.

Venkatesh, G. & Brattebo, H. 2011(c) Analysis of chemicals and energy consumption as cost components in water and wastewater treatment: Case study of Oslo. Norway. Urban Water Journal 8(3), 189-202.

Venkatesh, G., 2011, PhD thesis – Systems Performance Analysis of Oslo's Water and Wastewater System. Norwegian University of Science and Technology. Trondheim. Norway-7491. ISBN 978-82-471-2623-3. Accessible at <http://urn.kb.se/resolve?urn=urn:nbn:no:ntnu:diva-12664>

Venkatesh, G., Brattebo, H., 2011(b), Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway). Energy 36(2), 792-800.

Venkatesh, G., Brattebø, H., 2011(a). Environmental impact analysis of chemicals and energy consumption in wastewater treatment plants: Case study of Oslo. Norway. Water Science and Technology 63(5), 1018-1031.

Venkatesh, G., Brattebø, H., 2012(a). Assessment of environmental impacts of an ageing and saturated water supply pipeline network - City of Oslo. 1991-2006. Journal of Industrial Ecology 16(5), 722-734.

Venkatesh, G., Brattebø, H., 2012(b). Environmental impact analysis of chemicals and energy consumption in water treatment plants: Case study of Oslo. Norway. Water Science and Technology-Water Supply 12(2), 200-211.

Venkatesh, G., Hammervold, J., Brattebø, H., 2009. Combined MFA-LCA of wastewater pipeline networks: Case study of Oslo. Norway. Journal of Industrial Ecology 13(4), 532-549.

Venkatesh, G., Sægrov, S., Ugarelli, R. and Brattebø, H. (2014), WM2 and Dynamic Metabolism Model – Testing on Oslo’s water and wastewater system. TRUST deliverable D34.1.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TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

Scenario 2040
for Oslo as model city **D 34.2**

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