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Dynamic Metabolism Modeling as a Decision-Support Tool for Urban Water Utilities Applied to the Upstream of the Water System in Oslo, Norway

G. Venkatesh[a], R. Ugarelli[b]*, S. Sægrov[a], H. Brattebø[c]

[a]*Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway – 7491.*
[b]*SINTEF and Adjunct Professor, Department of Hydraulic and Environmental Engineering, NTNU, Trondheim, Norway – 7491*
[c]*Department of Energy and Process Engineering, Industrial Ecology Programme, Norwegian University of Science and Technology, Trondheim, Norway – 7491*

Abstract

The paper presents, first, the 'Dynamic Metabolism Model' (DMM), developed by the authors, followed by an application to the city of Oslo, capital city of Norway. The time period considered for the analysis is 2013-2043. The external factors impacting decision-making and interventions are talked about in brief, and some realistic scenarios revolving around these factors are drawn up for testing, after consultation with officials at the Oslo Water and Wastewater Works. Possible interventions that the utility intends to set in motion on the upstream are defined and numerically interpreted for incorporation into the DMM.

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Keywords: Dynamic modeling, urban metabolism, water treatment, water supply, water distribution

1. Introduction

Economical, demographic, behavioral and climatic changes are challenges that will not just impact the physical assets of water utilities, but will influence managerial approaches and require systems to be managed at an integrated level to ensure resilient, reliable and sustainable service in the short and in the long-term. The challenges faced by urban water utilities around the world today are multi-pronged and the nature of the demands the different stakeholders of the utilities (investors, operators, suppliers, managers, regulators and consumers) have is truly

* Corresponding author. Tel.: +47 454 29 787;
E-mail address: rita.ugarelli@sintef.no

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multifarious. While utilities exist primarily to fulfil the social functions of water supply and sanitation, there are additional requirements that they nowadays have to meet and focus on performing the previously mentioned vital functions economically. Infrastructure Asset Management (IAM) is an integrated set of processes to manage urban water systems with the aim to minimize the life-cycle costs of infrastructure assets, at an acceptable level of risk, while continuously delivering established levels of service [1]. To gravitate towards sustainable development, IAM needs to be guided by a well-defined business philosophy based on balanced, adaptive total quality management (balanced from the social, economic, asset, governance and environmental points of view), clear communication and data management [1]. 'Urban metabolism', understood and analysed using a plethora of industrial ecology tools like material flow analysis (MFA) and life cycle assessment (LCA), is now very much the stock-in-trade for water utilities and results for urban metabolism analysis are more and more incorporated into the IAM methodologies to support decision makers (cfr. www. Trust-i.net).

Oslo Water and Sewerage Works (VAV in Norwegian) are responsible for the provision of water and sanitation services to the 600.000 inhabitants of Oslo. Challenges to the city include the likely population growth, increasing urbanization and deterioration of water infrastructures.

Oslo main water sources are two surface water bodies, Maridalsvannet and Elvåga lakes, each connected to a water treatment works (WTW) and a service reservoir, together providing fresh water for Oslo city with 90% and 10% of total supply capacity, respectively. Both key water sources to the city are of limited capacity (120 and 13.8 million cubic metres (MCM), respectively) as well as the inflow (average of 287 and 12 MCM/year, respectively). Leakage from the sub-catchment pipelines is currently 22% of total water demand.

The sewer system of Oslo city is a mix of combined and separate systems (out of total length of sewers, 37% are combined sewers, 30% sanitary sewers and 33% storm sewers). Two wastewater treatment plants (WWTW) collect 63% and 27% of the produced wastewater, respectively for WWTW1 and WWTW2. Oslo VAV has developed a water cycle safety plan (WCSP) ([2], [3], [4]) and the study showed that most important challenges in the urban water system in Oslo are related to water supply, especially the lack of a robust water supply system. In the risk analysis carried out in the drinking water supply system, the higher risk associated with the most severe event identified was the lack of treated water to supply the city of Oslo due to under designed treatment plants. [5], [6], [7], [8], [9], [10] and [11] have studied the water-sanitation system in Oslo in detail. Using these studies as a 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. Integrated modelling of urban water systems has been around for some time now. The DMM is not proposed as an alternative to any of the existing integrated models. It is tailor-made to fulfil specific end-goals, and thereby it certainly has its own deficiencies, however, it is marked by flexibility, simplicity and ease of use that are treasured requirements for strategic level of analysis in IAM.

2. Methods

The adopted methodology consists on the computation of selected sustainability indicators with DMM and then in comparing their variation during the period of simulation from the current value for different scenarios of interventions.

The following chapter provides a short description of the DMM, which would enable readers to understand the flow of data and information towards the end-results that are subsequently useful for decision-making.

2.1. The Dynamic Metabolism Model

The DMM aims to be a simple, flexible and modifiable, user-friendly MS-Excel-based model which; i) accepts user-inputs in one single user-friendly Excel file, ii) uses inbuilt formulas, constants, and 'intermediate' files, and iii) enables the end-user to test the impacts of changes expected / planned / imagined in the future, on sustainability indicators.

The set of related files (all MS Excel files) in the DMM includes the following:

1. Notes, assumptions and guidelines
2. User control
3. Annual files named as ‘Start year.xls’, ‘Start_year_plus_1.xls’ and so on

   Each of the annual files has the following worksheets

   a. *System description*
   b. *Background data*
   c. *Raw water sources_1*
   d. *Water treatment_2*
   e. *Water distribution_3*
   f. *Wastewater transport_5*
   g. *Wastewater treatment_6*
   h. *Energy cost module*
   i. *Snapshot of results*
4. Final results comparison

From point (3) above, it is clear that the DMM works with lumped annual data, in its current version. There is of course scope for dealing with weekly or monthly data, if data availability permits and supports such an exercise. The data encompass the different flows of water and wastewater, resource consumption (chemicals, materials and energy), operational and maintenance expenditures, capital costs (depreciation and interest payments), energy generation within the system, water and wastewater quality parameters, sludge generation, sludge composition etc.

There are two files in the model that are to be handled and updated by the user. The one on the top – *Notes, assumptions…* - is a single Excel file, presents a brief description of the changes and alterations (interventions, in other words) which are tested for a given scenario by the end-user. The other user-interface Excel file is *User Control.xlsx.* This is an interactive Excel file, which the user needs to spend time working on, row by row, and define the changes and alterations he/she foresees and wishes to implement in the years to come. Some of these changes would be primary and others would be secondary. The secondary ones are automatically calculated by Excel. As the user works with this file, ensuring that all the annual files and the *Final results_comparison.xlsx* file are kept open, the annual files get updated automatically and the final results are computed and graphically depicted.

As indicated above, the annual files (3a-3f in the list above) are automatically populated with data entered by the user and calculated by Excel. The ‘f’ from each of these links up to the last file in the DMM – *Final results_comparisons.xlsx.* The final performance indicators are categorized into ‘economic’, ‘social’, ‘environmental’ and ‘functional’; and further into a per-capita-of-population and a per-cubic-metre-water-demand basis.

The final results are presented both as absolute values as well as values normalised with regard to the start-year (against which comparisons are made). The normalised values are also plotted on a line graph to provide a visual representation. The indicators – relative values – can be looked upon as the ‘semi-processed information’, as far as the final purpose of decision-making is concerned. Relevant decision-making-related information has to be teased out of this semi-processed information.

2.2. Scenarios and interventions

A scenario is a construct of the ‘action’ of external factors, which acting singly or in unison, influence decision-making regarding interventions in the future. The factors are identified as A (Population growth), B (Rise in industrial water demand), C (Asset deterioration) and D (Climate change). In line with the results from the WCSP, the focus was put on the upstream part of the system which includes raw water resources, water treatment and water distribution and on the comparison of alternative interventions dealing with the identified challenges. In addition a *status quo* situation, which does not take into consideration any of the factors is also analysed. Dialogue with the personnel of VAV allowed selecting the type of alternative interventions that should be prioritized at strategic level of planning, in case of occurrence of the above mentioned scenarios of change.

As given to understand from the Oslo Water and Wastewater Authority, the utility would, to be better prepared for temporary failures in the existing supply system which need to countered by having an alternative water source to kick in during the 'Time to Repair', like to increase the capacity of the water sources, as well as the WTP hydraulic capacity.

For the sake of this study, seven cases have been considered on the upstream side. Four discrete interventions are considered; and some of them are combined together to get three combinations; thus taking the total number of test-cases to seven. The factor A, population increase, is common to all these seven, with the population growth profile also remaining the same for all of them; this factor is considered to be the only one impacting decision-making. The population increase in this case is assumed to be non-uniform and sourced from [12]. The four discrete interventions on the upstream side, according to discussions with Oslo VAV, are as below:

a) Reduction in per-capita water demand (all demand excluding leakage) supplied by the WTPs from the current value, at a uniform rate of 1% per year, till year-2040. The decreases are assumed to be wrought by a combination of measures, and these details are not considered to be of relevance to the analysis.
b) Reduction in leakage from the network, at a rate of 1% per annum for the first 3 years of the time-period being studied, at an expenditure to the tune of 4.5 million NOK per year (in real currency units). According to sources at Oslo VAV, all the expenses would be directed to the salaries for 6 additional employees.
c) Installation of micro-turbines on the upstream to utilize the kinetic energy from water flowing downhill to the WTPs. 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)
d) The raw water is sourced from Holmsfjorden – 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 [12]. Holmsfjorden 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 these four cases, three combinations are considered: 'a+b', 'a+b+c' and 'a+b+d'.

3. Results and discussions

Appendix A lists the relative values for some of the metrics included in the model, for year-2040, for the seven cases analysed as well as for a so-called Zero Scenario where BAU conditions exist. The values are normalised with respect to year-2013, for which all indicators are valued as '1'.

As far as the GHG emissions per capita and acidification impact per capita are concerned, the effect of the combinations 'a+b', 'a+b+c', and 'a+b+d' on decreasing the value of the indicator in year-2040 with respect to the cases 'a', 'b', 'c' and 'd' are clearly seen. As far as per-capita eutrophication is concerned, the fact that the nitrogen and phosphorus loadings in the wastewater treatment plant increase in direct proportion to the population; and the fact that most of the eutrophication in the water-wastewater system is attributable to the treated effluent discharge to the sink, result in a near-constant value for all cases, which can also be observed in the Table. When it comes to indicators like energy and electricity consumption, and treatment chemicals use per capita, in cases 'a', 'a+b', 'a+b+c' and 'a+b+d', the common factor 'a' implies that the water consumption per capita (at the tap), decreases over time, even as the population keeps increasing. The denominator (population serviced) thereby increases at a much faster clip than the energy, electricity and chemicals drawn in by the system to treat the water reaching the users. Adding on 'b' which brings down the leakage to 18%, supplements this effect a bit.

Water supplied per capita per year shows an appreciable drop in cases 'a+b', 'a+b+c' and 'a+b+d', as mentioned earlier. As far as wastewater treated per capita is concerned, while the volumes handled are greater than the volumes of water supplied (as wastewater includes storm-water and sewage), the rate of increase in the volumes over time is lesser still than that of the water supplied by the water treatment plants. This is reflected in lower values for the indicator – wastewater handled per capita – in 2040, vis-à-vis water supplied per capita.

For the same reason as (and also due to the fact that) the energy, electricity and treatment chemicals consumption per capita drop, the net O&M expenses (real currency terms) per capita register a 35% drop. This is owing to, inter alia, the fact that the salaries and maintenance expenses in real terms are assumed to remain the same even as population increases. Also, the rise in net expenditure on energy is held back by the revenues earned by the sale of transport fuel, and electricity generated by micro-turbines (in some of the cases). In addition, the assumption that no new pipelines are installed after year-2013, means that energy consumption associated with pipeline installation (which dominates the lifecycle of pipelines in the network) is absent for the period 2014 to 2040.

In the cases 'd' and 'a+b+d', where a new water source is brought on-stream, the value of the indicator 'capital expenditure in 2040 (depreciation + interest) per capita', is greater than in year-2013. The 'income from water supply fees per capita' which would include the recovery of the capital investment and also the general operation and maintenance expenses incurred, is also correspondingly greater for the cases 'd' and 'a+b+d' vis-à-vis the other five cases. 'Income from sanitation fees per capita' remains almost the same for all the seven cases – a 40% drop from the 2013 level.

Knowledge of how the values change over time (the trend lines) should not be totally dispensed with. This has been incorporated in Figs 1, 2, 3 and 4; where the trends of two selected indicators – GHG emissions per cubic metre water demand & Capital expenditure per capita have been plotted. While Figs 1 and 2 pertain to GHG emissions per cubic metre, the last two pertain to Capital expenditure per capita.

When Figs 1 and 2 are considered together, the effect of a reduction in water demand (1% annually throughout the study period), seems to be very effective in reducing the GHG emissions per capita over time. Of course, during this period, the population also increases at a steady pace. 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). In Figs 3 and 4, it is evident that capital investments called for in 'd' (where a new water resource is brought on-stream, along with a new WTP and associated piping).

The exercise carried out in this paper, 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. 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 analyzed, vis-à-vis these targets.

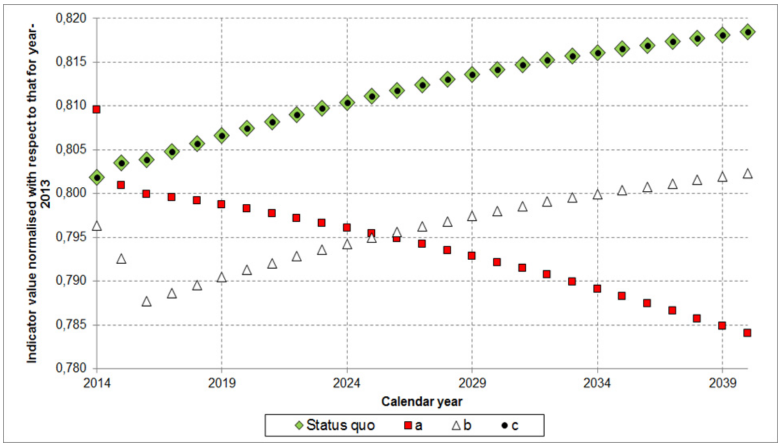

Fig. 1: Change in GHG emissions per capita (Status quo, 'a', 'b' and 'c')

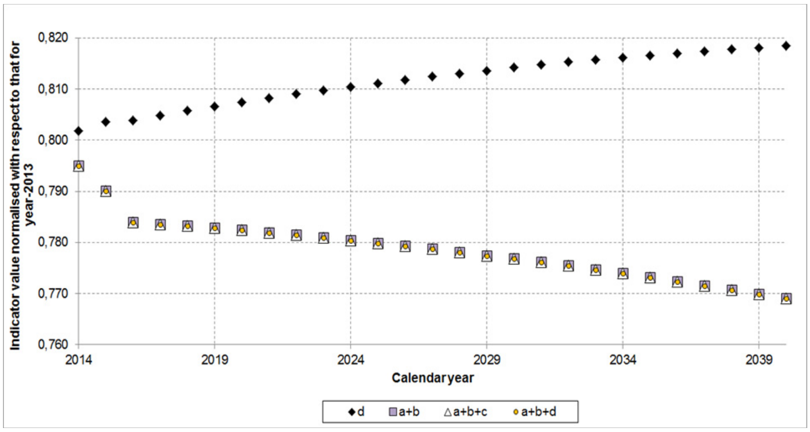

Fig. 2: Change in GHG emissions per capita (‘d’, ‘a+b’, ‘a+b+c’, ‘a+b+d’)

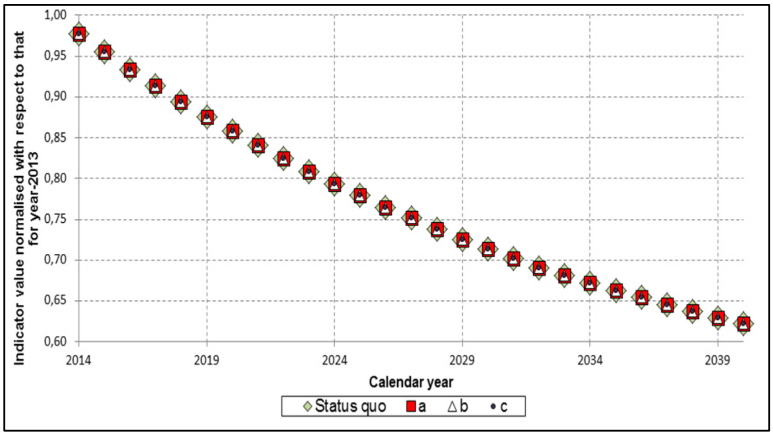

Fig. 3: Change in Capital expenditure per capita (Status quo, ‘a’, ‘b’ and ‘c’)

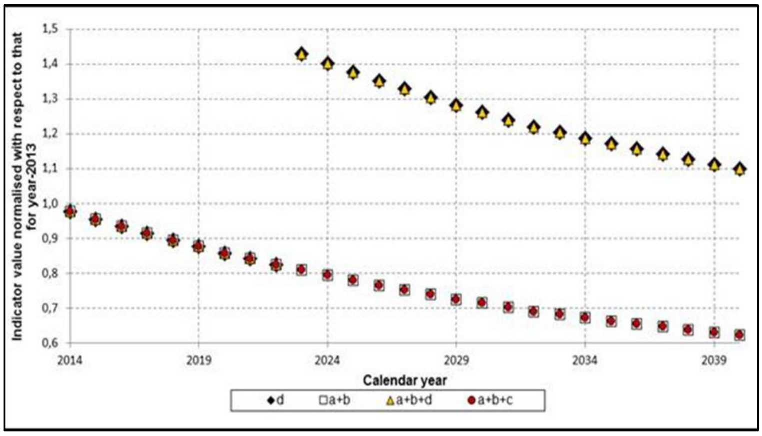

Fig. 4: Change in Capital expenditure per capita (Status quo, ‘d’, ‘a+b’, ‘a+b+c’, ‘a+b+d’)

4. Conclusions and further work

Four interventions and three combinations of interventions for the upstream were tested with the Oslo water and wastewater utility as a case. These interventions were constructed after consulting personnel at Oslo water utility. The Dynamic Metabolism Model, developed at the Norwegian University of Science and Technology was used to test these interventions. DMM is an integrated UWS, user-friendly and MS Excel-based model which can be easily populated. It calculates KPIs of the urban water system for specific point in time which would be either for today and in the long run for given scenarios. The DMM model also calculates the resources (e.g. chemicals, energy and materials) required for running the water and wastewater subsystems. It can be used for the entire city or sub-catchments and it is regarded as a valuable tool for strategic level of analysis in IAM

The results tabulated in Appendix A; and the sample graphs in Figs 1, 2, 3 and 4, present the findings of the tests performed for Oslo. Among the indicators listed, the utility may wish to zero in to a few key ones. As explained in the previous section, the purpose of this particular exercise was not to enable the utility to single out one set of interventions as the best way forward, but to compute and compare the selected indicators over time to gauge improvements.

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Appendix A. Selected indicator values in 2040 for the seven upstream cases (all values normalised with respect to year-2013)

Metric / Indicator	2040 Status quo/BAU scenario	2040 a	2040 b	2040 c	2040 d	2040 a+b	2040 a+b+c	2040 a+b+d
Environmental indicators								
GHG emissions per capita	0.818	0.784	0.802	0.818	0.818	0.769	0.769	0.769
Total energy consumption per capita	0.968	0.894	0.933	0.968	0.969	0.862	0.862	0.864
Total treatment chemicals consumption per capita	0.922	0.860	0.893	0.922	0.922	0.833	0.833	0.833
Total energy consumption per cubic metre water demand	0.968	0.970	0.969	0.968	0.969	0.971	0.971	0.972
Total treatment chemicals consumption per cubic metre water demand	0.922	0.933	0.927	0.922	0.922	0.938	0.938	0.938
Physical indicators								
Water supplied per cap per year	1.000	0.922	0.963	1.000	1.000	0.888	0.888	0.888

Wastewater treated per cap per year	0.863	0.813	0.840	0.863	0.863	0.792	0.792	0.792
Functional indicators								
Leakage percentage (%)	1.000	1.000	0.857	1.000	1.000	0.857	0.857	0.857
Economic indicators								
Income from water supply fees per capita of consumers with access	0.642	0.631	0.640	0.637	0.982	0.637	0.632	0.977
Income from sanitation fees per capita of consumers with access	0.638	0.635	0.637	0.638	0.638	0.633	0.633	0.633
O&M expenses per cubic metre water demand	0.687	0.724	0.706	0.687	0.687	0.752	0.752	0.752

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