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# TESTING DIFFERENT REHABILITATION OPTIONS IN THE DRINKING WATER PIPELINE NETWORK IN OSLO USING DYNAMIC METABOLISM MODEL (DMM)

## Utprøving av forskellige rehabiliteringsopsjoner i Oslos drikkevannledningsnettverket ved bruk av den dynamisk-metabolism-modellen (DMM)

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## Abstract

This study is being carried out at the behest of Oslo VAV (Vann og Avløpsetaten; Water and Sanitation Utility) personnel, as an additional test with the Dynamic Metabolism Model (DMM) developed at NTNU in Trondheim. It considers rehabilitation of drinking water pipelines as the only intervention in the entire system; and tests for different rehabilitation rates; 1 %, 1.25 %, 1.5 %, 2 %, 2.25 % and 2.5 %. A range of indicators for the water distribution sub-system are calculated for the study period 2013–2043. Of all the indicators for the entire system, calculated automatically by the DMM for these different rehabilitation rates, four are selected for tabular and graphical representation in this article. A rise in the rehabilitation rate from 1 % to 2.5 % has a conspicuous impact on the relative value of the GHG emissions per cubic metre water demand in 2043 – it falls from 0.822 to 0.772. The relative value of the total energy consumed in the entire system per capita in the year 2043 drops with a rise in the rehabilitation rate (0.86 for 1 % to 0.796 for 2.5 %). It will however not be possible to say what the optimum rehabilitation rate to be pursued is, 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). Setting targets and benchmarks to be achieved in the case of these indicators would also be useful.

*Key words* – Rehabilitation, replacement, water pipelines, Oslo, dynamic metabolism model

## Sammendrag

Denne studien utføres på oppdrag fra Oslo VAV som en tilleggstest med verktøyet "Dynamic Metabolism Model" (DMM) utviklet ved NTNU i Trondheim. Det vurderer renovering av drikkevannsledninger som eneste inngrep i hele systemet, og test av ulike renoveringsrater; 1 %, 1,25 %, 1,5 %, 2 %, 2,25 % og 2,5 %. En rekke indikatorer for vanndistribusjonssystemet er beregnet for perioden 2013–2043. Indikatorene regnes automatisk ut av DMM for ulike renoveringsrater, og i dette utvalget av indikatorer er fire valgt ut og presentert i figurer og tabeller i denne artikkelen. En økning i renoveringsraten fra 1 % to 2,5 % har en påfallende effekt på den relative verdien til denne indikatoren i år 2043 – den faller fra 0,822 til 0,772. Den relative verdien for den totale energibruken i hele systemet per person i 2043 synker med økende renoveringsgrad (0,86 for 1 % til 0,796 for 2,5 %). Det er derimot ikke mulig å forutsi hva som vil være den optimale renoveringsraten med mindre man vet hvilke indikatorer det vil arbeides med, og hvordan enheten rangerer/vekter disse. Det er et spørsmål om å betrakte ulike indikatorer av forskjellig slag – funksjonelle (renoveringsrate, lekkasjerate), miljømessige (klimagassutslipp, forsuring etc., per person), fysiske (muligens mengde material i rørledning per person, dersom en reduksjon i dette er en målsetting) og økonomiske (kapitalkostnader og drift- og vedlikeholdskostnader uttrykt ved egnede indikatorer). Det vil også være nyttig å fastsette mål og referansepunkter som ønskes oppnådd for disse indikatorene.

## Introduction

This study is being carried out at the behest of Oslo VAV (Oslo Vann og Avløpsetaten; Oslo's water and sanitation utility) personnel, as an additional test with the Dynamic Metabolism Model (DMM) developed at the Norwegian University of Technology in Trondheim, as part of the EU TRUST (Transition to the Urban Water Services of Tomorrow) project. It is a consequence of a meeting held at Oslo VAV on the 9th of May 2014 with Lars Hem, Jadranka Milina and Arnhild Krogh. Leakage control is a top priority in the agenda of Oslo's water utility. Efforts are on to zero in on optimum approaches to managing leakage in drinking water pipeline networks. While pressure management in the pipelines is understood to be effective in reducing leakage to some extent, the need for rehabilitating water pipelines cannot be overlooked. However, the benefits (monetary and otherwise) associated with rehabilitating pipelines need to be understood vis-à-vis the expenses (and environmental emissions) that would be incurred in the process (Venkatesh, 2012). The DMM models each sub-system of the water-wastewater system (water treatment, water distribution, consumption, wastewater collection and wastewater treatment and discharge) in Oslo separately; thus providing the possibility of following the effects of changes on a sub-system or the entire system. For more information about this model, readers may refer to Venkatesh et al. (2014).

In this paper, the methods adopted have been described in brief, followed by the results obtained and discussions thereabout. Finally, the report concludes with what the utility can glean from the results and how the DMM can be used for further analyses and tests.

## Methodology

Rehabilitation of drinking water pipelines entails either cast-in-pipe coating with polyurethane resin or replacement with a similar pipe. Resources are consumed during the process – diesel as an energy source, new pipelines when replacements are needed, and coating materials. The purchase of new pipes as replacements is considered as a capital investment, which is depreciated over the lifetimes of the pipes (105 years assumed for all polymer pipes; from Ugarelli et al. (2008)). Expenses on diesel, polyurethane resin and the service charges if any, to the personnel hired for carrying out the rehabilitation work count as O&M expenses. These are add-ons to the general maintenance expenses incurred on inspection of pipelines, and pumping stations, and the expenses on electricity for water pumping. In the model, the energy expenses are calculated separately and the expenses incurred on purchasing the resin are added on to the baseline maintenance expenditure (value of the start-year) which is assumed to also include all the service charges involved.

All data needed for this purpose were obtained from Oslo VAV (Lars Hem and Arnhild Krogh, in 2014) through personal communication at Oslo VAV and over the e-mail. Values for specific diesel consumption for rehabilitation and replacement, are the same as the ones used in the earlier tests carried out with the DMM and are ballpark estimates provided by Oslo VAV personnel (Per Kristiansen, in 2009; Venkatesh, 2011). Table 1 summarises the same. Table 2 lists the data for diesel consumption in installation and rehabilitation of pipelines. The prices of PE pipes used for replacement are obtained from Egeplast international GmbH, Greven, Germany (2013). For 100 mm diameter PE pipes, it is 29 Euros per metre, while for the 300 mm ones, it is 297 Euros per metre. Replacement 'expenses' are construed as capital investments and depreciated over a period of 105 years. Average diameters of 100 mm and 300 mm respectively are assumed for the small and medium diameter pipes replaced. The price of flexible liquid PU foam used for CIPP is 14 Euros per kilogram, as gathered from the Internet source – *http://www.business.com/guides/pricing-and-costs-of-polyurethane-foam-24935/*. The specific gravities of materials considered for the calculations are 0.93 for polyethylene, 1.05 for polyurethane, and 7.1 for both ductile iron and grey cast iron. The thickness of the polyurethane coating during CIPP is 2–4 mm (3 mm assumed as an average); the diameter-to-thickness ratio of PE pipes is 11, the thicknesses of grey cast iron pipes of 100 mm and 300 mm diameter are 9 mm and 13 mm respectively, while the corresponding values for the ductile iron pipes are 6 mm and 7.2 mm respectively (Venkatesh, et al, 2012)

From an e-mail correspondence from Lars Hem of Oslo VAV received in May 2014, the author could obtain a mathematical relationship between the rehabilita-

Table 1. *Data inputs to the DMM for this analysis on the water distribution sub-system (Sukumar Muthurajah and Lars Hem, 2014).*

| | Percentage CIPP 30 % | Percentage replaced 70 % |
|---|---|---|
| Small diameter pipelines | 5 % | 20 % |
| Medium diameter pipelines | 95 % | 80 % |

Table 2. *Data for diesel use in installation and rehabilitation (Venkatesh et al., 2012).*

| Description | Value (in litres per metre of pipe) |
|---|---|
| INSTALLATION OR REPLACEMENT | |
| Large-diameter (400 mm and greater) | 35 |
| Medium-diameter (200 mm to 399 mm) (Average of 300 mm; outer diameter for PE pipes) | 30 |
| Small-diameter (199 mm and less) (Average of 100 mm; outer diameter for PE pipes) | 25 |
| REHABILITATION | |
| Large-diameter (400 mm and greater) | 2 |
| Medium-diameter (200 mm to 399 mm) (Average of 300 mm; outer diameter for PE pipes) | 1.5 |
| Small-diameter (199 mm and less) (Average of 100 mm; outer diameter for PE pipes) | 1 |

tion rate and the leakage percentage (see Equation 1 below). As indicated, this is an empirical approach. The rehabilitation percentages considered in this exercise are 1 %, 1.25 %, 1.5 %, 2 % and 2.5 %. Rehabilitation of water pipelines is the only intervention considered in this exercise. The environmental data (specific emission values) recorded in the DMM were sourced from the Ecoinvent database (Swiss Centre for Lifecycle Inventories) of the LCA software SIMAPRO (PRe Consultants, 2008).

$$-\Delta \text{ leakage } (\%) = 5 * (\text{Total leakage as fraction}) * (\text{Rehab } \% - 0.5) \qquad (1)$$

Replacement is considered to be the same as installation except that there is no increment to the length of pipelines in the network. This is taken care of in the model, by considering both the removal of a pipe (indicated as metres disconnected from the network) and its replacement (addition of the same length back to the network). Further, under the assumption that there is no recycling or reuse of the pipe which is disconnected, the installation of the replacement-pipe is considered to be a net positive environmental burden, from a resource-consumption point-of-view. As per Oslo VAV, PE pipes replace ductile iron and grey cast iron pipes without lining. The kilometres replaced are assumed to be split equally between these two materials for small and medium size pipelines replaced, and the masses which exit the system (though they stay *sub-terra* and are not available for recycling or reuse) are calculated.

The rehabilitation rate is not entered as a percentage in the User Control file of the DMM. The lengths of pipelines rehabilitated – small, medium and large – are entered, while remembering that some of these can be replacements and therefore have to be considered as installations of new pipelines (duly balanced by removal of the same number of metres). This means that the enduser is expected to enter manually whatever relationship he/she would wish to consider – into the cells of the row which contains the leakage percentage values for each year. This would be done of course independent from entering the values of the lengths of pipelines, to be rehabilitated. This, one may safely say, may be roughly constant over time, as long as the rehabilitation percentage is maintained constant over the time-period.

The leakage percentage then feeds into the equations which calculate the water demand fulfilled by the water treatment plants (final consumption + leakage losses), and the volumes reaching the end-users (absolute and per-capita values).

Rehabilitation thus, in addition to holding back rapid ageing of the network (a replacement introduces a new pipe which replaces an old one), and adding to the capital value of the network, helps to bring down leakage and thus has beneficial effects upstream and downstream, as it decreases the volume of water which would otherwise have had to be treated. This translates into less consumption of chemicals and energy for treatment (and pumping), a control (not necessarily a decrease, but mostly a slowing down of the rate of increase when one considers a population growth as well over time) of the operational expenses and the upstream environmental impacts. Having said that, it has to be mentioned that the population growth forecast assumed here is from Paus and Hem (2012).

Thus, in addition to examining the trends in the indicators selected (Table 3) for the water distribution subsystem, it is also necessary and interesting to observe the changes in certain systemic indicators (for the entire system and not just the water distribution sub-system) like GHG emissions per capita, GHG emissions per cubic metre water demand, total treatment chemicals consumed per capita, and total energy consumption per capita. The next section presents the results of the tests carried out for the different rehabilitation percentages considered, as tables and graphs.

Table 3. *List of indicators considered for the water distribution sub-system alone [Colour codes differentiate among functional (brown), economic (yellow), environmental (green) and physical (grey) categories.]*

| | |
|---|---|
| GHG emissions per capita | Pipeline material mass per capita |
| Electricity consumption per capita | Length of pipelines per capita |
| Total energy consumption per capita | Water supplied per cap per year |
| GHG emissions per cubic metre demand | Leakage percentage (%) |
| Acidification impacts per cubic metre demand | O&M expenses per capita |
| Eutrophication impacts per cubic metre water demand | Capital expenditure per capita |
| Total energy consumption per cubic metre water demand | O&M expenses per cubic metre water demand |
| Electricity consumption per cubic metre water demand | Capital expenditure per cubic metre water demand |

## Results and discussions

Table 4 summarises the values of 16 different indicators relevant for the drinking water pipelines' sub-system, for year 2043, normalized with respect to year 2013 (for which values of all indicators are assumed to be equal to 1). These indicator values, it must be restated, are for the water pipeline sub-system only. As the rehabilitation rate rises from 1 % to 2.5 %, the relative value of GHG emissions per capita drops in 2043, from 0.751 to 0.672. The corresponding drop in the relative value of GHG emissions per cubic metre water demand is from 0.854 to 0.822. On the one hand, there is a drop in per-capita water demand supplied for all the six cases, owing to the reductive effect rehabilitation is expected to have on leakage. On the other, there is a steady rise in population. The rate of rise in the total water demand supplied is thus less than that in the population, explaining the lower relative values for the first indicator in Table 3, vis-à-vis GHG emissions per cubic metre water demand.

The reduction in leakage rates over time also holds back the rate at which the pumping energy increases (as it holds back the rise in water volumes to be pumped). The rate of increase in pumping energy consumption is thus lower than that of the population. This explains the drop in the value of the indicator – Electricity consumption per capita in the water distribution sub-system. Compared to a 12 % drop in the value of this indicator when the rehabilitation rate is 1 %, one could achieve an 18 % drop by increasing the rehabilitation rate to 2.5 %. The electricity for pumping accounts for a sizeable

Table 4. *Relative values in year-2043 for the different rehabilitation scenarios (normalised with respect to year 2013).*

| Indicator for the water distribution sub-system | Rehabilitation rate in % | | | | | |
|---|---|---|---|---|---|---|
| | 1 % | 1.25 % | 1.5 % | 2 % | 2.25 % | 2.5 % |
| GHG emissions per capita (kg carbon dioxide eq) | 0.751 | 0.724 | 0.706 | 0.684 | 0.677 | 0.672 |
| Electricity consumption per capita (kWh per cap) | 0.880 | 0.853 | 0.836 | 0.821 | 0.818 | 0.818 |
| Total energy consumption per capita (kWh) | 0.803 | 0.774 | 0.754 | 0.730 | 0.723 | 0.717 |
| Pipeline material mass per capita (kg) | 0.512 | 0.490 | 0.468 | 0.425 | 0.402 | 0.380 |
| Length of pipelines per capita (m) | 0.600 | 0.600 | 0.600 | 0.600 | 0.600 | 0.600 |
| Water supplied per cap per year (cubic metres) | 0.880 | 0.853 | 0.836 | 0.821 | 0.818 | 0.818 |
| Leakage percentage (%) | 0.468 | 0.318 | 0.215 | 0.096 | 0.064 | 0.042 |
| O&M expenses per capita (Euros) | 0.637 | 0.635 | 0.634 | 0.632 | 0.632 | 0.631 |
| Capital expenditure per capita (Euros) | 0.673 | 0.692 | 0.710 | 0.746 | 0.764 | 0.782 |
| O&M expenses per cubic metre water demand (Euros) | 0.724 | 0.745 | 0.758 | 0.770 | 0.772 | 0.772 |
| Capital expenditure per cubic metre water demand (Euros) | 0.766 | 0.812 | 0.849 | 0.909 | 0.934 | 0.957 |
| GHG emissions per cubic metre demand (kg carbon dioxide eq) | 0.854 | 0.849 | 0.844 | 0.833 | 0.828 | 0.822 |
| Acidification impacts per cubic metre demand (kg sulphur dioxide eq) | 0.682 | 0.703 | 0.717 | 0.730 | 0.733 | 0.733 |
| Eutrophication impacts per cubic metre water demand (kg phosphate eq) | 0.924 | 0.917 | 0.911 | 0.898 | 0.892 | 0.886 |
| Electricity consumption per cubic metre water demand (kWh) | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Total energy consumption per cubic metre water demand (kWh) | 0.913 | 0.907 | 0.902 | 0.889 | 0.883 | 0.877 |

chunk of the total energy consumption, with the diesel consumption for replacement, rehabilitation and maintenance accounting for a relatively-smaller proportion of the total. Addition of a constant consumption of diesel fuel (for rehabilitating a fixed length every year for a given rehabilitation rate), tends to lower the rate of increase of the numerator – total energy consumed in the sub-system – in this indicator, vis-à-vis that of the numerator in the indicator – electricity consumption per capita. This is reflected in the slightly lower relative values for the third indicator in Table 3 vis-à-vis the second.

The relative values for 'water demand supplied per capita' are the same as those for 'electricity consumption per capita', owing to the fact that the latter is simply a product of the former and a constant number representing the specific electricity consumption of the pumping system. Here, it needs to be pointed out that an assumption of constancy with regard to this value has been made. Owing to the fact that older grey cast iron and ductile iron pipelines are disconnected from the network, and relatively lighter polyethylene pipes are added on in lieu of those removed, the mass of active pipelines per capita drops appreciably over time. At a rehabilitation rate of 1 %, decrease of nearly 50 % is seen in this indicator value in 2043 vis-à-vis 2013. Increasing the rehabilitation rate to 2.5 %, cuts this down by over 60 %. If the assumed relationship between rehabilitation and leakage (Equation 1) holds good, a rise of the rehabilitation rate to 2.5 %, enables a 95.8 % reduction in the leakage share of the water demand supplied. This, though, is more theoretical than practical. Further, here we have not considered the effect of pressure management on leakage reduction. The value of the indicator 'O&M expenses per capita' drops significantly over time – by about 37 % over the 30-year period. It remains fairly the same though for all the rehabilitation rates, owing to the fact that the increment in operation and maintenance expenses courtesy the consumption of polyurethane and diesel fuel, for all the six cases, is a small percentage of the total (which includes expenditures incurred on pumping electricity, general maintenance and salaries). The effect of holding back the rise in the expenses on pumping electricity by rehabilitating more is also to be considered while analysing the behaviour of this particular indicator.

Owing to the fact that the average annual rate of increase in the population is greater than that in the total water demand supplied by the WTPs (thanks to the reduction in leakage and thereby a restraint on the rise in volumes of drinking water supplied), the relative values of the indicators denominated on the total water demand supplied, are less than the corresponding indicator denominated on the population. The value of 'O&M expenses per cubic metre water demand' in year-2043 increase as the rehabilitation rate rises, and tapers to a constant of around 0.772. (On a per-capita basis as indicated above, this remains fairly constant!)

Needless to say, the value of capital expenditure per cubic metre water demand (and per-capita) in 2043, increases with the rehabilitation rate (the replacement of ductile iron and grey cast iron pipes with PE pipes is considered in this exercise as a capital investment into the system, depreciated over a period of 105 years).

It is not just the end-values but also the paths followed by the indicators to their end-values which are important. There are surely different ways to get to the desired end-point, but one needs to choose the optimal-best path to get there. Figures 1, 2, 3 and 4 chart the paths for four selected indicators for the drinking water distribution sub-system – GHG emissions per capita per year, Water demand per capita per year, Annual capital

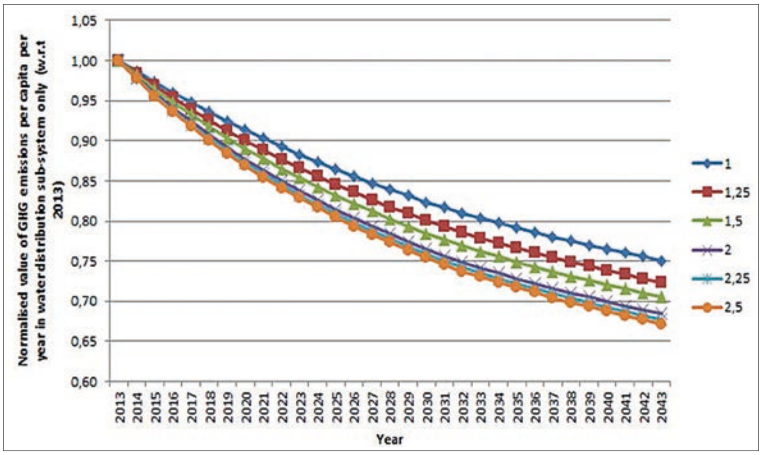

Figure 1. *Effect of degrees of rehabilitation on the GHG emissions per capita per year, in the water distribution system (Each line represents one particular annual rehabilitation percentage).*

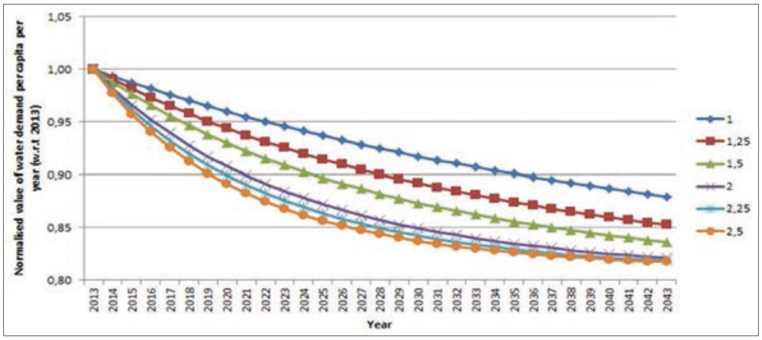

Figure 2. *Effect of degrees of rehabilitation on the water demand per capita per year, in the water distribution system (Each line represents one particular annual rehabilitation percentage).*

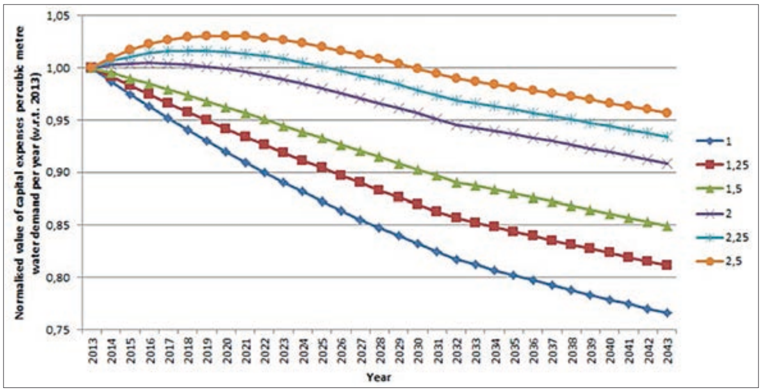

Figure 3. *Effect of degrees of rehabilitation on the annual capital expenditure per cubic metre water demand in the water distribution system (Each line represents one particular annual rehabilitation percentage).*

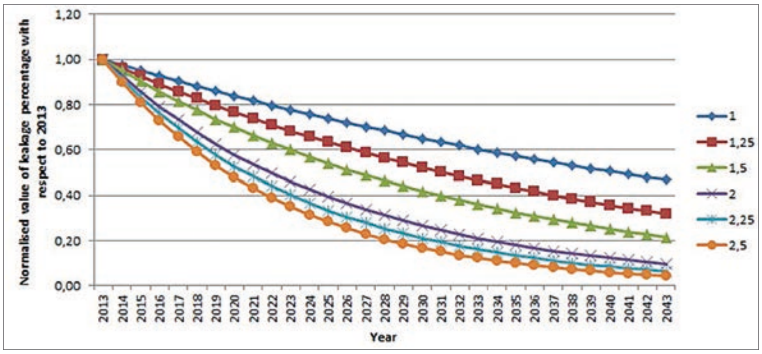

Figure 4. *Effect of degrees of rehabilitation on the percentage leakage from the water pipelines (Each line represents one particular annual rehabilitation percentage).*

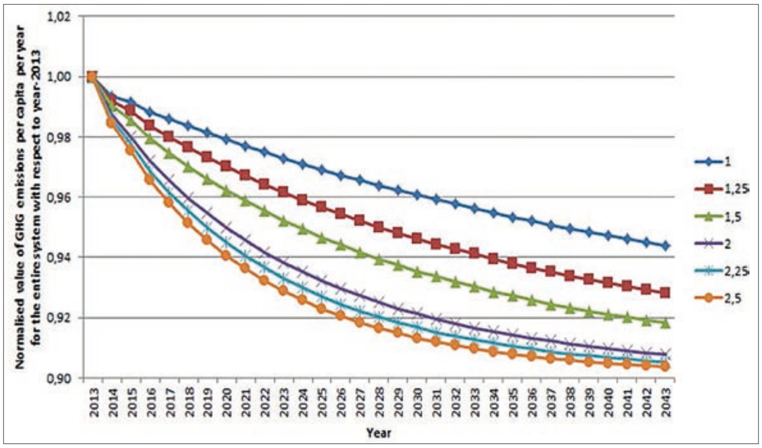

Figure 5. *Effect of degrees of rehabilitation on the GHG emissions per capita in the entire system (Each line represents one particular annual rehabilitation percentage).*

Table 5. *Relative values in year-2043 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 (kg carbon dioxide eq) | 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 (kg carbon dioxide eq) | 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 |

expenditure per cubic metre demand, and Leakage percentage. Note the initial upturn in the value of the indicator 'Capital expenses per cubic metre water demand', for rehabilitation rates 2 % and greater, before the curve dips down below 1.

In Table 5, 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-2043 – it falls from 0.822 to 0.772.

The value of the first indicator in Table 4 drops over the 30-year 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

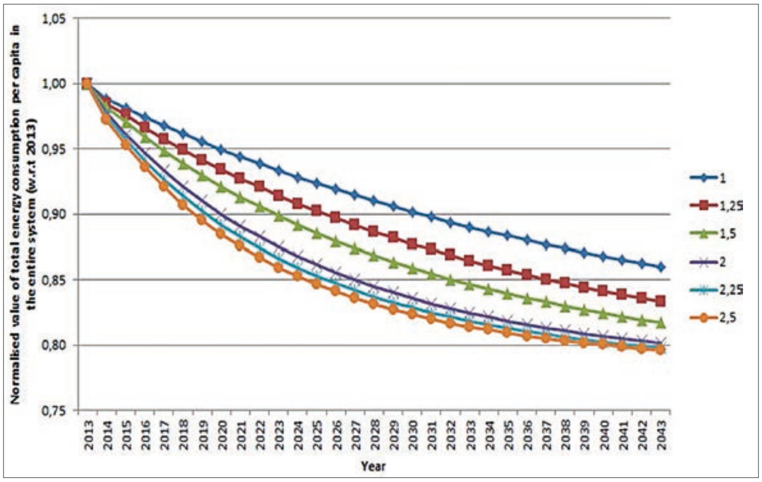

Figure 6. *Effect of degrees of rehabilitation on the total energy consumption per capita in the entire system (Each line represents one particular annual rehabilitation percentage).*

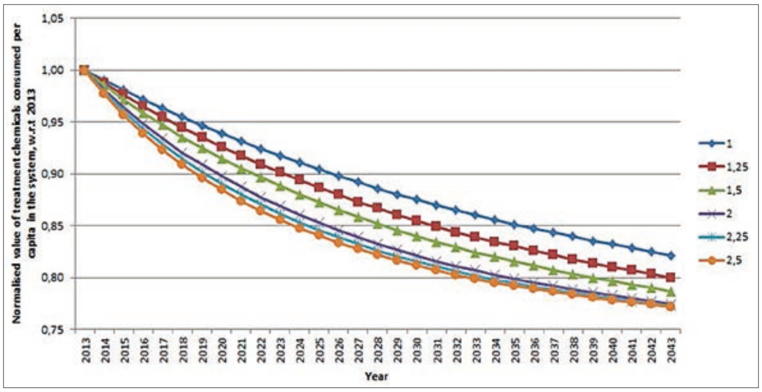

Figure 7. *Effect of degrees of rehabilitation on the masses of treatment chemicals consumed per year per capita (Each line represents one particular annual rehabilitation percentage).*

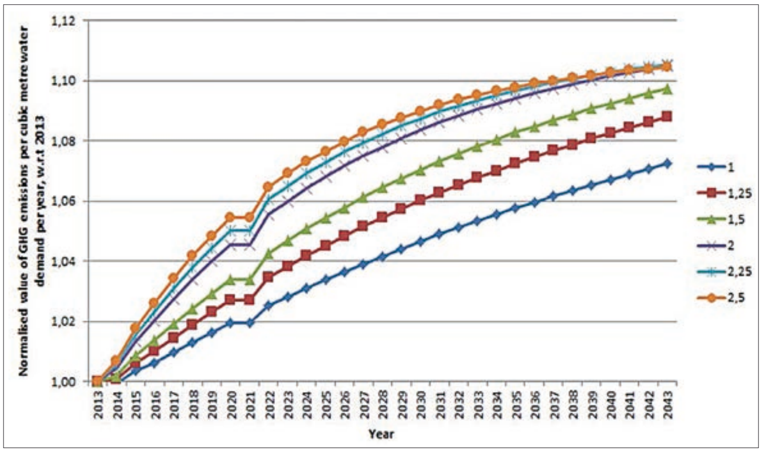

Figure 8. *Effect of degrees of rehabilitation on the GHG emissions per cubic metre water demand in the entire system (Each line represents one particular annual rehabilitation percentage).*

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, PE and PU. 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 the year 2043 drops with a rise in the rehabilitation rate (0.86 for 1 % to 0.796 for 2.5 %).

## Conclusions

It is to be noted that rehabilitation of drinking water pipelines is the only intervention considered in this article. This can be tested in tandem with other interventions as well, and their combined effect on the systemic indicators can be analysed.

Referring back to the 'Methodology' section, one will note that data have been gathered from various sources, and some reasonable assumptions and estimates have also been made in the absence of documented data. The final results – indicator values – are sensitive to different extents to the input data variables. Improving the accuracy of the latter will obviously lead to more reliable outputs from the DMM.

Again, it will not be possible to say what the optimum rehabilitation rate to be pursued is, 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). Setting targets and benchmarks to be achieved in the case of these indicators would also be useful.

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