

Decision Support Tool for Optimal Water Meter Replacement

Harrison E. Mutikanga^{1,4,5}, Kalanithy Vairavamoorthy^{2,1,4}, Frank Kizito⁵ and Saroj.K. Sharma³

¹UNESCO-IHE Institute for Water Education, P.O.Box 3015, 2601 DA Delft, The Netherlands.

Corresponding author email: h.mutikanga@unesco-ihe.org

²Professor and Chair of Water Engineering, School of Civil Engineering, University of Birmingham, Edgbaston Birmingham B15 2TT, United Kingdom.

³Senior Lecturer, Department of Urban Water Supply, UNESCO-IHE Institute for Water Education, P.O.Box 3015, 2601 DA Delft, The Netherlands.

⁴Delft University of Technology, Delft, The Netherlands

⁵National Water and Sewerage Corporation, Kampala, Uganda

ABSTRACT

The main challenge facing water utilities in developing countries is how to cope with the deterioration of service-based assets such as water meters amidst constrained budgets. Meters decline in accuracy with usage over time, resulting in significant revenue losses for the utility and inequitable customer billing. These utilities often lack tools to support management decision making on optimal meter replacement to maximize revenues and reduce utility metering costs. In this paper, a model is developed for optimal replacement period of customer water meters. The Model is based on life-cycle costing methodology and uses net present value techniques to economically optimize the replacement frequency for individual meters of size 15 mm. The developed model is automated and uses MS-Access® as a platform. It is linked to the customer information database to provide a dynamic replacement schedule based on cumulative volume through the meter and predicted meter accuracy degradation rate. The model was applied to Kampala City in Uganda using real-world water utility data for budgetary planning and prioritizing meter replacements. Using sensitivity analysis, it is established that optimal meter replacement period is strongly influenced by the water price and the meter degradation rate *inter alia*.

Keywords: Decision Support Tool; Life-cycle Costing; Meter Replacement; Water Utilities

1.0 INTRODUCTION

The water meter is an essential tool for both the utility and the customers to measure and monitor consumption. In universally metered utilities, the water meter acts as a utility's "cash register" and generates all revenues needed for system maintenance and infrastructure improvements. When metering is inefficient and coupled with low tariffs, the financial sustainability of utilities is at stake. A large proportion of meters used in urban water utilities are the small size meters of 15-mm (1/2") usually installed to measure consumption for domestic and small commercial properties. In Kampala, Uganda, these small size meters make up about 94% of all customer meters and generate about 70% of total revenues. Like all mechanical devices, water meters typically decline in accuracy with usage over time causing substantial revenue losses to the utility and gives rise to unequal billing policy. National Water and Sewerage Corporation (NWSC)-Uganda is operating at a global metering accuracy of about 79% in Kampala City (Mutikanga *et al.*, 2010) while in Canal de Isabel water utility in Madrid, Spain, domestic water meters (DN 13-40 mm) have been reported to be operating at an average global metering accuracy of about 86% (Flores and Diaz, 2009). A 20% loss in accuracy for a domestic meter, with an average monthly bill of \$ 20, would result in annual revenue loss of \$48. For a city like Kampala with over 100,000 such meters, the utility loses about \$ 5 million per year due to metering inaccuracy. Where utilities charge for sewerage services based on volume of water registered through the meter, the losses could be substantial. Since significant revenues are lost through degraded meters, optimal meter replacement is very essential for water utilities. In water engineering, optimal scheduling of asset replacement and rehabilitation using life-cycle costing (LCC) has been studied and

documented by many researchers (Kleiner *et al.*, 1988; Dandy & Engelhardt, 2006; Jayaram & Srinivasan, 2008). The water meter replacement problem has been attempted in the past by a number of researchers (Noss *et al.*, 1987; Lund, 1988; Allander, 1996; Yee, 1999; Egbaras & Tennakoon, 2005; Hill & Davis, 2005) based on the foundation methodology proposed by American Water Works Association (AWWA, 1966) for determination of economic period for water meter replacement. This paper contributes to the literature of optimal water meter replacement strategies by developing a model that combines meter performance over time with life-cycle costs (LCC). The net present value (NPV) approach is adopted in selecting the optimal meter replacement period with minimal costs to the utility over the planning period. For the first time, the salvage value of the replaced meter is included in the optimal decision. A real world water utility case study is used to illustrate application of the developed tool.

2.0 THE OPTIMAL METER REPLACEMENT MODEL (I-WAMRM)

The optimal meter replacement tool, referred to here as “I-WAMRM” is developed to determine the individual water meter optimal replacement period based on totalized registered volume through the meter. It is now generally accepted that it is usage and not time that is responsible for wear and tear to occur (Wallace & Wheadon, 1986; Hill & Davis, 2005). Most previously developed tools were based on meter age and not usage, and did not account for the time value of money in the replacement decisions. The model is developed specifically for optimal replacement of multi-jet velocity meter types. In the Kampala water network, revenue water losses in multi-jet meters is mainly due to loss of meter accuracy with time as opposed to complete failure of the meter (stuck register of a working meter unable to measure flow). However, when dealing with the positive displacement (piston-type) meters with high failure rates, the failure costs must be incorporated in the model using appropriate methodologies (Noss *et al.*, 1987; Lund, 1988). Failure is mainly due to sand and other particulates that get lodged into the moving gear parts and the clearance between the piston and measuring chamber halting the meter from measuring flows (Richards *et al.*, 2010). This is more pronounced in poorly managed networks with positive displacement (piston-type) customer meters. For example in Kampala City an average of 1,300 meters per month were reported stuck by meter readers according to the call-centre monthly reports of August-October 2010. The optimal replacement period (ORP) is found by minimizing the total annual costs of replacement defined as:

1. Cost of replacement policy (CRP): the cost of removing, testing, repairing, replacing and disposing meters.
2. Cost of water lost through failed meters (CWLF): water used but not measured after failure and before repair.
3. Cost of water lost through inaccurate meters (CWLI): derived from accuracy versus usage relationships.

The total annual cost (TAC) is calculated as follows:

$$TAC = CRP + CWLF + CWL I \quad (1)$$

2.1 Framework of I-WAMRM

The optimal meter replacement period has been defined as the time when revenue loss due to a drop in accuracy equals cost of replacing a meter (Wallace and Wheadon, 1986). The condition driving the decision to replace the i th asset has been defined by Ugarelli and Di Federico, 2010 as:

$$CT_i(n) - [IN_i(n) + D_i(n)] \geq 0 \quad (2)$$

Equation 2 states that at stage n , if the costs to maintain the existing i th asset (CT_i) are greater than the cost of investing in a new asset (IN_i), including the eventual depreciation charge of the existing asset (D_i), the asset should be replaced. The utility's objective is to minimize the sum of these costs over an infinite number of succession replacement periods as in classical regeneration problems (Lund, 1988; Arregui *et al.*, 2006; Arregui *et al.*, 2010) shown in Figure 1. This is referred to as the minimum net present value cost of the replacement chain (MNPVC_n).

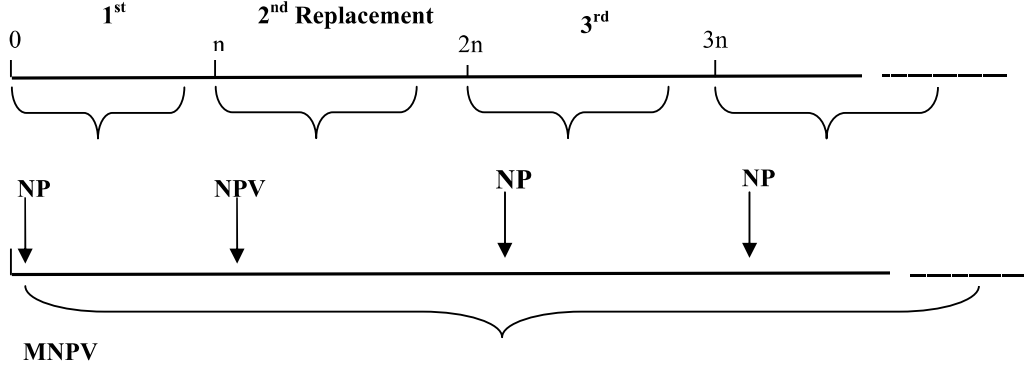


Figure 1: Minimum Net Present Value Costs of the Replacement Chain

2.2 Net Present Value of the Life Cycle Costs

The LCC seeks to optimize the costs of acquiring, owning and operating physical assets over their useful lives by attempting to identify and quantify all the significant costs involved in that life, using the present value technique. LCC enables the trade-off between costs and benefits during the asset life to be studied to ensure optimal selection (Woodward, 1997). The elements of LCC for a water meter have been identified as: (i) initial costs of meters; (ii) cost of meter replacement; (iii) administrative (information and feedback) costs; (iv) meter under-registration costs; and (v) disposal costs. Since the operation and maintenance costs for the selected small water meter model (multi-jet or single-jet velocity type meters) are negligible, equation 1 becomes:

$$TAC = CRP + CWL \quad (3)$$

where $CRP = [(C_{IN} + C_{INST} + C_{Admin}) - C_{SV}]$ and $CWL = \sum_{t=1}^n \frac{P_w Q_t \varepsilon_t}{(1 + r')^{t-1}}$

and n is the number of years for the meter replacement period, r' is the real discount rate, C_{IN} , C_{INST} , C_{Admin} is the cost of meter purchase, installation and initial administrative costs, P_w is the price of water ($\$/m^3$) and assumed to be constant throughout the analysis period, Q_t is the average volume of water consumed by the user in the year t , ε_t is the weighted meter error, C_{SV} is the salvage value of the meter often sold as scrap at disposal time and is a function of meter material (plastic or bronze). Meters with bronze housings are sold as raw materials for steel industries but plastic meter bodies are hardly bought and their salvage value could be neglected. Finally, the minimum present value cost of this infinite series of replacement is given by:

$$MNPVC_n = [CRP + CWL] \left[\frac{(1 + r')^n}{(1 + r')^n - 1} \right] \quad (4)$$

Equation 4 is the main engine of the optimal meter replacement model in selecting a period n that minimizes the total costs (or maximizes the revenues). The model calculates the NPV of the costs of infinite replacements conducted at fixed time steps. The period n is constant over the present and future replacement periods provided real costs and interest rates remain constant.

2.3 The Real Discount Rate (r')

The real discount rate is given by the Fisher Equation (Fisher, 1930 as cited in Ugarelli & Di Federico, 2010):

$$r' = \frac{1 + i_R}{1 + I} - 1 \quad (5)$$

As the life cycle costs are discounted to their present value, selection of a suitable discount rate is a crucial decision in LCC analysis. In the case of water meters, since the investment is reasonably risk free, the discount rate used will be quite close to the ones set by each country as risk free rates or state bonds (Arregui *et al.*, 2006). The appropriate discount rate should be determined by the utility's corporate planning department rather than mere arbitrary selection.

2.4 Model Application to Case Study of Kampala City, Uganda

National Water and Sewerage Corporation (NWSC), Uganda, had 146,063 metered customer connections in Kampala city as at end of June 2010. About 94% of all meters installed in Kampala City (or 137,300 meters) are of sizes 15 mm (1/2-inch) and are mainly used for measuring water use for residential (domestic) and small commercial properties. The corporation adopted a policy of universal customer metering in 1991 and meter coverage in the city is 100%. The average age of the installed meters is about 10 years with the oldest meters almost 20 years now. Unlike in most developed countries, there is no regulation in Uganda that requires utilities to test and replace meters after a certain period of time. Meters are replaced only when they are stolen or vandalized or on a run-to-fail basis and are reported by meter readers or customers. The total replacement value for these meters is conservatively estimated at US\$ 4 million which is a substantial amount. Clearly, most meters are approaching the end of their useful lives and there is need for developing a more proactive water meter replacement strategy. The challenge is how to optimally carry out meter replacement with limited financial resources and this paper attempts to address this problem.

2.5 Predicting Water Meter Accuracy

Most problems in operations research and engineering involve establishing the relationship between two or more variables. Regression analysis is the statistical technique that is often used for such types of problems (Montgomery and Runger, 2007). An important aspect of predictive models is to be able to predict how condition will deteriorate over time. Water meter accuracy degradation is a function of many variables and it is not easy to predict meter performance with certainty. However, it is important to understand the meter accuracy degradation process in every metering strategy. Many researchers have assumed a linear relationship between accuracy and age or cumulative volume through the meter for domestic small meters (Noss *et al.*, 1987, Hills & Davis, 2005; Arregui *et al.*, 2006). Pasanisi and Parent (2004) studied meters' degradation using a Markovian Dynamic Model, based on four discrete states, each of which characterizes a more inaccurate metrology. Inference calculations are made in a Bayesian Framework by the Markov Chain Monte Carlo (MCMC) techniques. In this study a regression analysis has been used assuming a linear relationship to predict meter accuracy degradation rate due to its simplicity. Based on statistical random sampling techniques and meter testing records from a recently established database in the Kampala meter testing laboratory, data for a total of 122 meters was analyzed. Out of the 122 data sets, only 83 were finally used after data filtering of suspicious outliers. The fitted simple linear regression model (with the coefficients reported to two decimal places) for the multi-jet velocity meter model for Kampala City that relates water meter accuracy to volume is:

$$A = -0.003v + 95.94 \quad (6)$$

Where, A is meter accuracy (%) and v is the totalized registered volume through (m^3).

The sample of meters tested and analyzed were of size 15 mm and of different age (usage) groups selected from different geographical zones of the water distribution network to ensure fair representation of network characteristics (time in service, water quality, user profiles etc). The goodness of fit of the regression line which is measured using the coefficient of determination ($R^2 = 67.2\%$) is rather low due to uncertainties of input data in predicting the water meter accuracy degradation rate. In addition, other key factors such as water quality characteristics were not included in the model due to inadequate reliable data. The authors are working together with the utility management to establish a more accurate and comprehensive

meter management database. Arregui *et al* (2009) recommended the use of a software tool (Woltmann) that has been designed specifically for improving water meter management. A rich database of both customer use demand profiles and accurate meter testing results will improve the value of R . However, the regression model in Equation 6 can be used to fairly predict average weighted water meter accuracy based on meter condition (totalized registered volume at any time t as an indicator).

2.6 Defining Utility Parameters for the Model

The utility model input data is summarized in Table 1. The multi-jet meter model is the subject of analysis; however any other meter could be used for evaluation depending on reliable data availability.

Table 1: Kampala Water Utility Parameters

Water price (US\$/m ³)	1
Interest rate (%)	10
Inflation rate (%)	6
Real discount rate (%)	3.8
Average annual consumption per user (m ³)	variable
Multi-jet water meter (Metrology)	Class C, DN 15 mm, Q _n = 1.5 m ³ /h
New Meter Retail Price (US\$)	30
Removal and Installation Costs (US\$)	10
Administrative Costs(US\$)	3
Salvage Value (US\$)	3
Initial weighted error (%)	-4
Weighted error rate of decay (%/year)	-0.3

3.0 Numerical Results and Discussions

The results of the model for the selected two individual meters are summarized in Table 2. From Table 2, meter A is within the optimality replacement volume range (1386-1848 m³) or a frequency of every 7 to 9 years and needs to be replaced now before the cost of water loss due to meter inaccuracy exceeds replacement costs. At 9 years, the Billing index (BI) is 1848 m³ and the total cost is US\$ 557. So it does not make much difference whether Meter A is replaced after 7, 8 or 9 years as the incremental cost is minimal. Meter B has far exceeded the optimality billing index and should be a priority for replacement. At a billing index of 10,912 m³, the total cost to the utility is US\$ 2,879 which is more than twice the cost at optimality of US\$1,278. For both, meters, about 30% of the total cost is due to meter replacement activities and 70% is revenue lost as a result of meter under-registration.

Table 2: Summary of I-WAMRM Predicted Optimal Metering Conditions

Parameter	Meter Number	
	96-712461(A)	96-638391(B)
Average annual consumption (m ³ /year)	231	579
Current Meter Reading or Billing index (m ³)	1,741	10,912
Billing index at optimality (m ³)	1,386	1,158
Average accuracy at optimality (%)	91.8	92.5
Optimal meter replacement period (years)	7	3
Total cost at optimality (US\$)	551	1,278

3.1 Sensitivity Analysis

In both the LCC and regression analysis models, uncertainties are not accounted for in an explicit manner. However, the disadvantage is partially compensated for by a sensitivity

analysis. Sensitivity analysis was performed with respect to (i) meter degradation rate, and (ii) cost of water. The sensitivity results for meter A are presented in figures 2a and b.

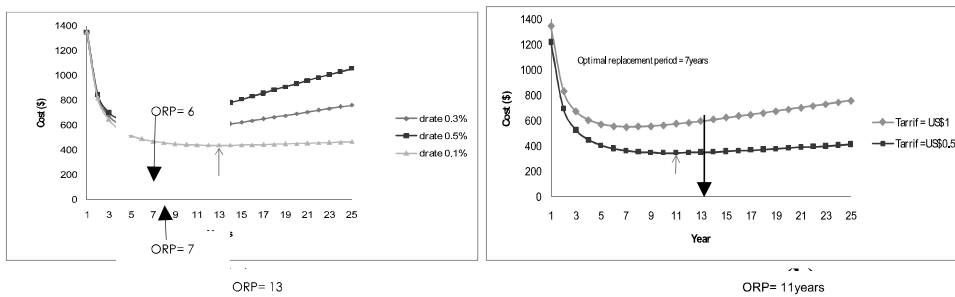


Figure 2: Influence of Accuracy Degradation Rate and Tariff on ORP

As depicted in figure 2a, the meter degradation rate of the weighted accuracy has a major influence on the ORP. By changing the degradation rate from 0.3% per year to 0.1% per year increases ORP by almost twice from 7 years to 13 years. Therefore it is important to ensure that input data (customer demand profiles and test bench results) used to generate the meter degradation rate of the weighted accuracy is very accurate, reliable and representative of all meters or different cohorts of meters. The price of water has a significant influence on the ORP as indicated in Figure 2b. Reducing the cost of water by half from US\$ 1 to US\$ 0.5 per m³, extends ORP by 5 years. The result is straight forward, when the cost of water increases, the meter ORP happens sooner to minimize costs. Although I-WAMRM is a useful tool to support meter management decisions, it requires costly establishment of consumption pattern and meters' error curves standardised databases which may be out of reach for many small water utilities in the developing countries with often limited resources. To address this a more simplified tool based on comparison of monthly billed volumes through the meter and historical average billed consumption of several years was developed to support small water utilities improve water meter management. Due to limitations of space, it was not possible to present details of the tool in this paper. The tools can be provided on request from National Water and Sewerage Corporation-Uganda or UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

4.0 CONCLUSIONS

This paper presents a cost-based model for optimal replacement period of DN 15 mm water meter sizes using existing scientific tools and operations research techniques. The meter testing data is used to establish the relationship between meter performance and usage. The optimal meter replacement period is calculated based on life cycle costs of water loss due to metering inaccuracy and cost of meter replacement including the salvage value of the meter. To minimize revenue water losses due to metering, multiple selection criteria including life-cycle costing should be adopted as opposed to sole criteria of low initial meter price that is often used in meter selection decisions. Sensitivity analysis was carried out to assess the impact of certain input variables on the optimal meter replacement period. The results indicate that the ORP is very sensitive to the price of water and the meter degradation rate of weighted accuracy versus usage.

5.0 ACKNOWLEDGMENTS

This work was funded under the Netherlands Fellowship Program and partially by National Water and Sewerage Corporation, Uganda. The authors are grateful to NWSC-Kampala Office staff for their support particularly Engineers Ameda and Feriha. The authors are also grateful to Maureen Hodgins of Water Research Foundation (Denver, Colorado), Allan Wyte (RTI International, USA) and Dr. Apollo Tutesigensi of Leeds University (UK) for their material support. Finally we thank Olivia Nantongo of Makerere University, Kampala who contributed to this work as part of her Master's program.

6 REFERENCES

- Allander, H. D. (1996) Determining the economical optimum life of residential water meters. *Water Engineering and Management*, 143(9), 20-24.
- Arregui, F., Cobacho, R., Soriano, J., and Garcia-Serra, J. (2010) Calculating the Optimum Level of Apparent Losses due to Water Meter Inaccuracies. *6th IWA Water Loss Reduction Specialist Conference* Sao Paulo, Brazil, CD-ROM.
- Arregui, F., Jr., C. E., and Cobacho, R. (2006) *Integrated Water Meter Management* IWA Publishing, London.
- Arregui, F. J., Martinez, B., Soriano, J., and Parra, J. C. (2009) Tools for Improving Decision Making in Water Meter Management. *5th IWA Water Loss Reduction Specialist Conference*, Cape Town, SA.
- AWWA (1966) Determination of Economic Period for Water Meter Replacement. *Journal American Water Works Association*, 58(6), 642-650.
- Dandy, G. C., and Engelhardt (2006) Multi-Objective Trade-offs between Cost and Reliability in the Replacement of Water Mains. *Journal of Water Resources Planning and Management*, 132(2), 79-88.
- Egbars, C., and Tennakoon, J. (2005) Ipswich Water's Meter Replacement Strategy. *Water Asset Management International*, 19-21.
- Flores, and Diaz (2009) Meter assessment in Madrid. *Efficient 2009*, Sydney, Australia, CD-ROM.
- Hill, C., and Davis, S. E. (2005) Economics of Domestic Residential Water Meter Replacement Based on Cumulative Volume. *AWWA Annual Conference*, San Francisco, California, CD ROM.
- Jayaram, N., and Srinivasan, K. (2008) Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. *Water Resources Research*, 44, doi:10.1029/2006WR005316
- Kleiner, Y., Adams, B. J., and Rogers, J. S. (1988) Selection and scheduling of rehabilitation alternatives for water distribution systems. *Water Resources Research*, 34(8), 2053-2061.
- Lund, J. R. (1988) Metering Utility Services: Evaluation and Maintenance. *Water Resources Research*, 24(6), 802-816.
- Montgomery, D. C., and Runger, G. C. (2007) *Applied Statistics and Probability for Engineers, Fourth Edition*, John Wiley and Sons, Inc, Arizona State University, USA.
- Mutikanga, H. E., Sharma, S. K., and Vairavamoorthy, K. (2010) Assessment of Apparent Losses in Urban Water Systems. *Journal of Water and Environment*. doi:10.1111/j.1747-6593.2010.00225.x.
- Noss, R. R., Newman, G. J., and Male, J. W. (1987) Optimal Testing Frequency for Domestic Water Meters. *Journal of Water Resources Planning and Management*, 113(1), 1-14.
- Pasanisi, A., and Parent, E. (2004) Bayesian Modelling of water meters ageing by mixing classes of devices of different states of degradation. *Applied Statistics Review*, 52(1), 39-65 (in French).
- Richards, G. L., Johnson, M. C., and Barfuss, S. L. (2010) Apparent losses caused by water meter inaccuracies at ultralow flows. *Journal of American Water Works Association*, 105(5), 123-132.
- Ugarelli, R., and Di Federico, V. (2010) Optimal Scheduling of Replacement and Rehabilitation in Wastewater Pipeline Networks. *J. of Water Resources Planning and Management*, 136(3), 348-356.
- Wallace, L. P., and Wheadon, D. A. (1986) An Optimal Meter Change-out Program for Water Utilities. *AWWA Annual Conference*, Denver, Colorado, 1035-1042.
- Woodward, D. G. (1997) Life cycle costing - theory, information acquisition and application. *International Journal of Project Management*, 15(6), 335-344.
- Yee, M. D. (1999) Economic Analysis for Replacing Residential Meters. *Journal American Water Works Association*, 91(7), 72-77.