Providing a targeted algorithm for replacing customers' Water meters aiming at reducing NRW: case study

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Abstract. Limited water resources, especially in Iran, which has an arid/semi-arid climate, highlight the need for accuracy in managing and controlling the consumption of this vital fluid. Although many approaches have been developed to reduce Non-Revenue Water (NRW) in water distribution systems, less attention has been paid to optimal prioritization for water meter replacement. In this research, an algorithm has been presented for the purposeful replacement of customers' water meters to increase the company's revenue. Gavankola village has been selected as a rural network in northern Iran with a high NRW rate (58\%) as a case study. Examining the customers' water consumption in 20 periods, it was found that after replacing the water meter, the billed metered consumption (BMC) doubled and the revenue from it increased up to 5 times. Moreover, the study of two economic indicators and NRW revealed that class C water meters are less economical than class B water meters, even though they more effectively reduce apparent losses.

Keywords: Apparent losses, WM replacement algorithm, NRW, Consumption Schedules, water companies.

1. Introduction

Non-Revenue Water (NRW) is one of the most important water programs in the world. NRW represents the water that is delivered but not sold to customers. According to the WHO/UNICEF Joint Monitoring Program, the annual volume of NRW has been estimated to be 126 billion m\(^3\), equivalent to $ 39 billion worldwide [1]. Apparent losses (AL) are among the first set of indicators in NRW that demonstrate a general management perspective on water efficiency and effectiveness, so-called basic indicators (level one) and have an effect on system management [2]. In general, AL includes water theft, billing errors, measuring instrument errors, human errors, management errors and operating errors. While these first factors are directly related to the management of water facilities and may be reduced by improving company procedures, WM errors are the most significant and difficult ones to determine the quantity. WM errors are amplified in networks vulnerable to water shortages, where users use private storage tanks to deal with intermittent water supply [3].
Measurement error is one of the most important components of AL that directly affects sales with revenue [4]. Water meters (WMs) are one of the most important tools to measure flow in the network [5]. Awareness of water companies about the amount of water produced and the total volume of water entering the network and BMC is crucial. In this regard, the accuracy of WM is of utmost importance [6]. Since the major share of water companies' revenues is provided through customers' cost water, the existence of low-precision WM can be an important factor in reducing revenue. Moreover, due to the inaccurate WM, the correct estimation of BMC and planning to supply water resources is disrupted and causes a lot of damage to infrastructure assets [7]. Therefore, it is necessary to test the accuracy of installed and new WM in accordance with a regular schedule and if necessary, they should be replaced. By replacing the customers' WM and increasing the accuracy of the WM operation, the measured costs will become real, and as a result, the revenues of water companies will increase, and the loss will decrease [8]. A comprehensive review of research in this field has been presented in Table (1). Due to the similarity of consumption culture and economic conditions of water companies and the type of household WM used, the most important studies in Iran and Islamic countries have been collected.

|previous study (year) | objective and parameters |
|----------------------|--------------------------|
|London, UK (2006) [9] | Investigating AL and identifying the main causes of WM inaccuracy |
|Ferrara, Italy (2007) [4] | Presenting 5-step basic strategies to control AL |
|Palermo, Italy (2009) [10] | Identifying the effects of private storage tanks on AL and identifying the ascending relationship between the two parameters of WM life and WM error |
|Kerman, Iran (2011) [11] | Investigating the increase in BMC and consequently the increase in water price compared to the WM failure period |
|Patiala, India (2012) [12] | Conducting research and development on methods, calibration, and measurement facilities and regulating water flow in WM based on statistical methods |
|Mohali, India (2013) [13] | Designing, developing, and presenting the benefits of automatic WM and employing economic analysis to replace WM in a variety of uses |
|Lithuania, Vilnius (2014) [14] | Analyzing accuracy of Class B and C WM and the effect of each on AL reduction |
|Pretoria, South Africa (2015) [15] | Investigating AL due to measurement error, the relationship between WM life, WM error and BMC records and analyzing experimental data |
|Pretoria, South Africa (2015) [16] | Investigating the accuracy of smart WM and their effect on reducing NRW and analyzing the cost of installation and operation |
|Borazjan, Iran (2016) [17] | Determining consumption schedules and conducting an economic analysis of WMR and determining the relationship between replacement time and WM life |
|Bushehr, Iran (2017) [18] | Analyzing the cost and revenue due to replacement of faulty WM and reduction rate of NRW |
|Tehran, Iran (2018) [19] | Evaluation of testing household WM with BMC less than ten m³/month in reducing AL |
|Johannesburg, South Africa (2018) [20] | Improving the data collection process from customers' WM and developing new methods in reducing AL of countries |
|Bialystok, Poland (2018) [21] | Optimizing WM measurements and the effect of WM diameter on the accuracy of WM and NRW |
|Isfahan, Iran (2018) [22] | Cluster testing of WM and investigating the effect of class, function, life, and diameter of WM on WM accuracy |
|Antalya, Turkey (2020) [23] | Experimental analysis of the effect of different types of household WM with different classes and the amount of pressure and water flow on the accuracy of the WM |
|Samarang, Indonesia (2021) [24] | Determining the effect of faulty WM, pipes leakage before installing WM, and water quality on AL of low consumption customers |
|Bandang, Indonesia (2021) [25] | Identifying the types of data processing errors in the study area and the feasibility of setting up Internet remote reading system of WM |
In previous studies, most efforts have been made to improve WM accuracy and reduce NRW. However, few studies have evaluated the effects of replacement prioritization and class WM accuracy. This study proposes an algorithm to assess the accuracy and replacement of customers' WM. One of the most important ways to increase the accuracy and become closer to realizing the results of this algorithm is to compare in a system. The region selected for the case study in this study is located in a rural climate with tourist attractions that have been less addressed in previous studies. Changes in the reduction of NRW and the increase in the revenue of the water company because of Water meter replacement (WMR) with different classes have been examined. In addition, changes in customers’ consumption categories and replacement costs are considered. Assessing the probabilities of failure and relative error of the WM is another issue under consideration.

2. Case Study
The case study of this research is the network of Shirdarkola and Gavankola villages in Babol city in northern Iran. Mazandaran Province Water and Wastewater Company responsible for water supply and service of these villages. These villages are in good weather condition so that they have a tourist attraction and some of its customers are only among the water consumers on weekends. According to the tank outputs, the network is divided into four isolated zones (DMA), which can be seen in Figure (1). According to the measurements, the average inlet water entering the network is 17 Ls-1 and the selling flow rate is 7.2 Ls-1. The NRW rate in this network is 58%, which is much higher than the World Bank standard (23%) [26]. Based on the data, the percentage of WMR rate in villages was about 3.5% from 2017 to 2020. However, the minimum percentage of WMR rate and its accuracy assessment in networks with high loss is estimated at 5% [1]. Therefore, it is necessary to take measures to reduce the amount of NRW caused by WM errors and to reduce AL in these villages.

The number of village’s customers in districts A, B, C and D were 423, 514, 240 and 413, respectively. These villages have 1590 subscribers, 94% of which are household customers.

Figure (2) shows the average BMC. As observed in the figure, about 60% of customers have an average BMC of less than 10 m³/month¹. Since most of the customers in the villages are single units, BMC less than ten m³/month¹ can indicate the probability of WM failure as well as the high rate of NRW [27]. The status of customers' WM based on WM life is shown in Figure (3). As can be seen from the figure, about 60% of the customers have a WM life of over 15 years. While the useful life of WM is between 8 to 10 years depending on the operating and climatic conditions [28].
3. Research method

The primary purpose of this study is to determine the priorities for replacing faulty WMs in order to reduce NRW. This section has introduced the algorithm to evaluate the accuracy and replacement of faulty WMs (Figure 4). The basis for designing the introduced criteria is in previous studies (Table 1). The first step in replacing the WM is identifying the WM conditions based on BMC records, WM life and cluster testing [1]. The World Bank standard recommends performing cluster testing by selecting at least one percent of consumers’ WMs [1]. Due to low manufacturing standards and the high average age of WMs in Iran, this value has been recommended to be 1 to 2.5 percent [29]. The WM status is detected first. Then, if the WM is defective, we act based on BMC records [30]. If the water WM is ok, we act in accordance with the life of the WMs. It should be noted that the life of the WM is not the only determining of failure and factors such as material, quality of consuming materials, climatic conditions, and accuracy will affect the manufacturing of the WM [9]. Prioritization for testing residential WMs is that residential WM testing with an average BMC between zero and 5 m$^3$ month$^{-1}$ is the top priority. BMC between 5 to 10 m$^3$ month$^{-1}$ is the second priority. Non-residential WMs (commercial, educational, public, etc.) will be evaluated as household WMs based on the type of use and under different defined tariffs and standards in water companies [23]. According to the Operational Regulations of Iran, the intended range for WMs errors in their replacement is 5% [29].

The data of this study were collected through customers’ bills using software in Mazandaran Water Company. Primary information gathered includes the customer’s first name and last name, file number, connection installation date, WMR date, WM body number, BMC average, WM size, number of units, username and reading status.

**Figure 2.** Average BMC of customers

**Figure 3.** Status of customers’ WMs

**Figure 4.** Algorithm for assessing the accuracy and priority of WM replacement
3.1. Identifying the risks of WM failure

Any device such as a WM can be defective. It is necessary to evaluate the probability and consequences of WM failure and defects to assess possible losses. Since the failure of a WM is a discrete event, it often occurs independently and continuously over time. The Poisson model (Equation 1) determines the probability of WM failure [31].

\[ p_t = 1 - \exp(-BR_{ij} \times t_i) \]  

In this formula, the BR parameter is the annualized failure rate (AFR) of WM i with class j. Moreover, the parameter P indicates the probability of WM failure i at time t (year). In this equation, t can also be regarded as a replacing index (representation) of the WM’s operating year. According to the previous studies, the failure rate of the WM class and the life of the WM were assumed to be the constant values of 0.01 and 0.066, respectively [31]. In terms of the consequences of failure, the detection of more vulnerable WMs can lead to better management of the AL due to WM error. According to the rationale, the failure of the WMs will increase as the water count increases [31].

3.2. Relative WM error against WM life and total recorded water volume

To examine the relative error of the WM and determine its trend, the total volume of BMC during different years is recorded and classified based on the life of the WMs. The relative error of the WM is determined according to the following relation [32]:

\[ \varepsilon_t = \frac{V_t - V_a}{V_a} \]  

In this formula, the parameter \( \varepsilon_t \) represents the relative error of the WM, the parameter \( V_a \) represents the actual volume measured by the new WM, and the parameter \( V_t \) represents the amount of volume indicated by the old WM. Then, the relevant fraction can be converted into a decimal, where a negative value indicates that the WM gives a reading less than the actual consumption and a positive value means that the WM provides reading with more than the actual consumption [32].

4. Results and discussion

Over the last 15 years, 125 residential WMs have been replaced in the villages. In order to compare BMC and the revenue impacts of WMR with pre-replacement conditions, the performance of 48 replaced WMs in 2017 was reviewed. The minimum period for comparing and reviewing the costs consumption before and after WMR is three periods [33]. In this study, in order to increase the accuracy of BMC data, data were collected in 10 periods before and ten periods after WM replacement. The number of replaced meters in districts A, B, C and D were 14, 15, 8 and 11, respectively. All replaced WMs were Class B and one-half inches and were for household usage.

4.1. BMC analysis

Figure (5) shows the average BMC before and after replacement based on WM life. According to the figure, the life of the WMs of these customers in two categories was between 5 to 10 years and 15 to 20 years. This trend indicates that WM life alone is not the cause of WM failure because 10% of the first category WMs failed during their useful life. It is also observed that as the WM life increases, the average BMC decreases. However, after the replacement, the average BMC increases drastically. This is due to the increased accuracy of the WM, which increases the revenue of the water company.

Figure 6 shows the share of BMC classes before and after WM replacement. According to the figure, about 55% of customers have a BMC below ten m\(^3\)/month\(^1\) before WM replacement. Therefore, it can be concluded that the two parameters of WM life and reviewing BMC records alone cannot be the determining parameters for WM replacement. Consequently, it is necessary to identify eligible customers based on these two parameters to achieve the desired results. Then the cluster testing of the WM should be performed and if the WM accuracy is low, it should be replaced. It is worth noting that as the BMC classes change, not only is the volume of NRW reduced but also there is a significant increase in revenue of the water company. This is because the price of water changes exponentially as
the BMC class changes and the cost of one m$^3$ of water in the class 0-5 m$^3$ month$^{-1}$ is not the same as the cost of one cubic meter of water in class 5-10 m$^3$ month$^{-1}$. Figure 7 clearly shows the displacement of the BMC classes. In addition to the monthly increase in total BMC, the decrease in the share of the first BMC (0-5) and second BMC (5-10) classes and the increase in the share of the fourth (15-20), fifth (20-25), sixth (25-30), and the seventh (30-35) BMC classes is evident in this figure. Finally, based on the combination of the two diagrams in Figures (5) and (6), the average changes in BMC before and after WMs' replacement were calculated to be 9.63 and 19.28 m$^3$ month$^{-1}$, respectively. Therefore, the results indicate a 100% increase in BMC after WMs replacement of these customers.

Furthermore, the effect of the accuracy of Class B and Class C WMs on BMC after the replacement has been evaluated. According to Figure. 7, due to the higher accuracy of the Class C WM than the Class B WMs, the NRW rate decreases more. By replacing the WMs of these customers with Class C WMs, BMC 2044 m$^3$ will increase annually. In other words, the amount of BMC per WM increases by one m$^3$ month$^{-1}$. The results have been consistent with the global standard of accuracy of WM classes, OIML R49-1 [34], because of the higher accuracy of class C WMs. Therefore, it is logical to use Class C WMs to reduce NRW.

![Figure 5. Average BMC before and after replacement based on WM life](image1)

![Figure 6. Share of BMC classes before and after WM replacement](image2)

![Figure 7. Effect of WM class on BMC of each region after replacement](image3)

4.2. Determining the probability of WMs' failure in Shirdarkola and Gavankola villages

In this section, the probability of WM failure is evaluated based on the WM life. Field studies show that all residential WMs used in the study region are class B and multi Jet dry WM. Based on the available records of the number of failures, the BR parameter was developed for these intended WMs and then was used to calculate the probability of the WMs' failure and fracture according to Equation (1). Figure 8 shows the failure probabilities of residential WMs of the village's customers in different
years. The results reveal that the probability of WM failure highly depends on the BR value related to the class and type of WM and the WM life. In the present study, the minimum and maximum values of the probability of WM failure during the WM life of 1 to 20 years have been evaluated to be 0.0145 and 0.9398, respectively.

4.3. Estimation of relative WM error
Relative WM error was analyzed for all replaced WMs in villages. As shown in Figure 9, the volume of BMC increases as the WM life increases. The pattern shows exponential growth. Growth in all cases of WM life is considered one year, which has a moderate and steady growth and reaches its peak in WMs with a life of 20 years. The minimum and maximum amounts of total water volume recorded are 1721 and 15594 m$^3$, respectively. If we analyze consumer information and add it as input, we expect this correlation diagram to improve.

4.4. NRW and Economic Analysis
As 48 WMs were replaced, the annual water sales increased from 5550 to 11107 m$^3$ (almost doubled). In addition to an increase in the BMC, the WMR has another benefit for the company, which is the increase in the price of water by changing the BMC classes. The amount of this increase in revenue for the villages is as shown in Table (2). The company had an annual income of approximately 86 Euros before replacing the WMs of these customers. However, after replacing these WMs, the water price received by the company is about 417 Euros per year, i.e., an increase of more than five times. However, the average selling price of water in Iran is 5500 Rials (0.0188 Euros) per cubic meter of water. Moreover, with the changes in BMC classes, the average selling price of water for these customers increased by 141%. It is predicted that by replacing all the priority, WMs of these villages (according to the algorithm), an annual income increase of 1000 Euros will be created.

Figure (10) shows a comparison between replacement and revenue with the WM class. The cost of WMR for WM Classes of B and C (based on the catalog of Iranensheab Company) is estimated at 1.8 and 2.8 million Rials, respectively [35]. According to this table, the return on investment (ROI) of the customers' WMR plan using Class B and Class C WMs is 8 and 13 months, respectively. Therefore, it can be concluded that if the company aims to reduce NRW, it is recommended to use class C WMs due to their high accuracy. It should be noted that Class C WMs are highly dependent on water quality and often have a shorter service life than Class B WMs. If the company's priority is in economic terms and return profit, it is better to use class B WMs because it has more economic benefits.
Table 2. Increase in water prices in accordance with the changes in BMC classes

| Consumption Schedules (m³month⁻¹) | Number of Customers | Old WMs | New WMs |
|----------------------------------|---------------------|---------|---------|
|                                  | BMC (m³year⁻¹) | Annual income (Euro) | Number of Customers | BMC (m³year⁻¹) | Annual income (Euro) |
| 0-5                              | 12             | 236     | 2.3    | 0             | 0     | 0.0    |
| 5,10                             | 14             | 1316    | 6.7    | 7             | 792   | 3.4    |
| 10,15                            | 13             | 1906    | 18.8   | 9             | 1420  | 13.0   |
| 15-20                            | 5              | 986     | 16.2   | 15            | 3067  | 48.7   |
| 20-25                            | 3              | 793     | 23.7   | 6             | 1579  | 47.3   |
| 25-30                            | 1              | 313     | 18.5   | 3             | 1014  | 55.5   |
| 30-35                            | 0              | 0       | 0.0    | 8             | 3235  | 249.2  |
| Total                            | 48             | 5550    | 86.3   | 48            | 11107 | 417.1  |

Figure 10. Comparison between replacement cost and annual revenue based on WM class

5. Conclusion
In this article, an algorithm was designed to replace and evaluate the accuracy of WMs and was implemented for the villages of Shirdarkola and Gavankola with 1590 customers as the study area. BMC customers whose WMs were replaced in 2017 were reviewed for 20 periods. The results were presented in three sections: BMC analysis, economic analysis and NRW analysis. The most significant achievements of this study are as follows:

- With the purposeful replacement of the customers' WMs, the BMC amount doubled and the NRW value decreased from 58% to 15%.
- It was specified that there is a direct relationship between WM life and BMC reduction.
- Replacing a Class C WM with a Class B WM will increase BMC and decrease NRW. However, if the goal is to achieve a lower return on investment, Class B WMs is more appropriate because of the lower purchase cost.
- The customers' WMR rates were analyzed in different years. It turned out that NRW caused by WM error in these villages should be a significant number. It was shown that the water company needs to take more effective measures to reduce AL.
- Although it was specified that testing and replacing customers' WMs with water consumption of more than ten m³month⁻¹ makes BMC closer to the actual consumption, it has no economic justification.
- Although older WMs are more likely to fail, this is highly dependent on the BR value of the WM classes and their types.
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