Case Analysis and Development Suggestions on China's Water Loss Control by Minimum Night Flow

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Abstract: Using minimum night flow (MNF) to determine leakage is an efficient method in District Metered Area (DMA), in which short-time inference is more useful and convenient base on the analysis with the comparison of hourly statistics. The case analysis shows the accuracy and effectiveness of short-time inference are mainly interfered by the precision of data recording system and the matching degree (Ma) between the minimum flow and the diameter of metering equipment in the DMA's inlets. Due to the current state of affairs in China, it is not feasible to immediately upgrade data precision; therefore, it is suggested that one could combine hourly statistics and improving Ma values in the application process of leak determination. Moreover, it is also necessary to promote the popularization of short-time inference through upgraded metering and recording equipment precision.

1 INTRODUCTION

1.1 The Basic Theory of Minimum Night Flow

Multi-stage metering division system is recognized as an efficient means for leakage control in large-scale water distribution system (Perelman and Ostfeld 2012), in which District Metered Area (Referred to as the DMA) is the most important basic unit (He 2018). Moreover, leakage detection is carried out frequently within the DMA (Thornton 2003), while the method to evaluate whether leakage exists in the DMA depends more on MNF (Lin 2011).

In recent years, with improvement in measuring accuracy of flow metering equipment in the water distribution system, criteria for MNF are also changing constantly.

Differing from the IWA definition (Al-Washali, Sharma and Kennedy 2016), China calculates MNF (Q_{MNF}) using the customer's normal night-time water consumption (Q_{NC}), the detectable leakage (Q_{DL}) (Buchberger and Nadimpalli 2004; Li et al. 2020) and the undetectable leakage (also termed background leakage (Liang and Wang 2017)) (Q_{UD}), thus $Q_{MNF}=Q_{NC}+Q_{DL}+Q_{UD}$ (Li et al. 2018).

Conventional MNF theory holds that during the night, due to reduced human activities leading to decreased water consumption, there exists a lowest water consumption time at night. Moreover, under the same water supply pipe network conditions, it is believed that the background leakage (Q_{UD}) should be stable (Al-Washali et al. 2020) and the customer's normal night-time water consumption (Q_{NC}) should correlate seasonally (Zheng et al. 2021) in the same region. Therefore, the MNF's standard value (Q_{SMNF}) fixed for a season of a single DMA can be expressed as "$Q_{SMNF}= Q_{NC}+Q_{UD}$" without detectable leakage. If the water supply pipe network conditions are changed, such as the case of new leakage points, MNF will change and the variable value is the detectable leakage in the DMA's water supply pipe network which can be calculate as "$Q_{DL}= Q_{MNF}-Q_{NC}-Q_{UD}= Q_{MNF}-Q_{SMNF}$."

It is impossible to accurately obtain the customer's normal night-time water consumption and background leakage of a single DMA due to the limitation of technical conditions and economic benefits. However, the total MNF can be measured

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by metering equipment installed at DMA entry, and the variable value before and after the occurrence of a new leak can be calculated (Buchberger and Nadimpalli 2004). Therefore, the difficulty of judging whether a leakage occurred or not is shifted to determining the MNF's standard value in different seasons at a single DMA.

1.2 Common Methods Using MNF for Leakage Detection in China

Although most research in the industry set MNF's standard value based on historical monitoring combined with confidence intervals (Buchberger and Nadimpalli 2004; Alkasseh et al. 2013; Farah and Shahrou 2017) , due to the complexity and prolongation of the process, the calculated value based on the staged monitoring are adopted as the MNF's standard value more often than not. Accounting for China's domestic application development situation, the common methods to use MNF for leakage determination include Interpolation between different sequences, Hourly statistics and Short-time inference.

Interpolation between different sequences calculates the detectable leakage by using the difference between the average NFM value for N consecutive days before and after the selected observation day (symbolized by $\overline{Q}_b$ and $\overline{Q}_a$) (Li 2017). As shown in Fig. 1, if a new leak occurs on the observed day, there are the following corresponding quantitative and calculation relationship:

$\overline{Q}_b = Q_{SMNF}$, $\overline{Q}_a = Q_{MNF}$, $Qd = \overline{Q}_b + Q_{DL}$

and $Q_{DL} = Q_{MNF} - Q_{SMNF} = \overline{Q}_a - \overline{Q}_b$

Although this method can effectively reduce disturbance caused by MNF fluctuation, the selection of N value requires long-term testing and continuous monitoring data.

Hourly statistics is to compare the measured MNF (Q_{MNF}) with the preset MNF's standard value (Q_{SMNF}) in the absence of detectable leakage. When $Q_{MNF} > Q_{SMNF}$, a new leakage is determined, and the detected leakage (Q_{DL}) is the difference between Q_{MNF} and Q_{SMNF}. According to the above MNF theory, the difficulty of this method is to determine a reasonable Q_{SMNF} value, as the customer's normal night-time water consumption and background leakage will fluctuate with seasonal changes and other conditions, thus Q_{SMNF} will need to be updated with actual data in any given DMA.

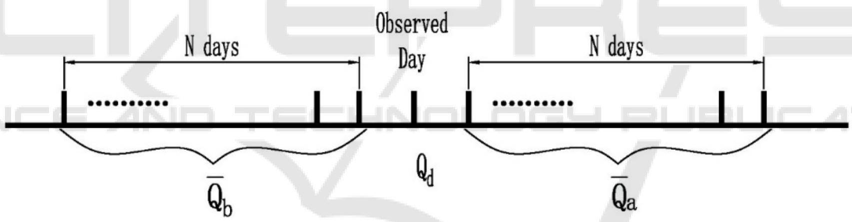

Figure 1: Graphical illustration of Interpolation between different sequences.

Short-time inference is an improvement on Hourly statistics. By shortening MNF observation interval to 2min, 5min and 15min, the disturbance of the customer's normal night-time water consumption is reduced as much as possible, so that the metered Q_{SMNF} is approximately equal to Q_{UD} (Buchberger and Nadimpalli 2004; Janković-Nišić et al. 2004; Covas, Jacob and Ramos 2008). Due to the relatively uniform characteristics and the elongated stability in a single DMA, it is easy and quick to evaluate background leakage. Therefore, it reduces both time and difficulty to gain MNF's standard value (Q_{SMNF}).

Although short-time inference will simplify Q_{SMNF}'s acquisition and improve the efficiency of leakage determination in a single DMA, its actual application effect remains to be confirmed due to less practical experience (Dai and Liu 2016) especially under the current flow measurement method in water distribution system. The following case study on application effect will concretely analyze the advantages and disadvantages of short-time inference comparing to hourly statistics in order to raise some improvement measures.

2 METHODOLOGY, DATA AND RESULT

2.1 Design of Research Experiment

As shown in Figure 2, the internal water distribution system of a single DMA is composed of municipal water supply pipe network and secondary water supply pipe network. There are two DN200 inlets of the municipal network with water meters installed to the north and south of the DMA. One DN150 inlet water meter is installed before the water pump of the secondary network, which can reflect the actual water consumption since the secondary water supply uses the pressure-superposed mode under the condition of controlled water loss of the pump. Thus this DMA's Q_{MNF} can be measured and calculated through the above three water meters.

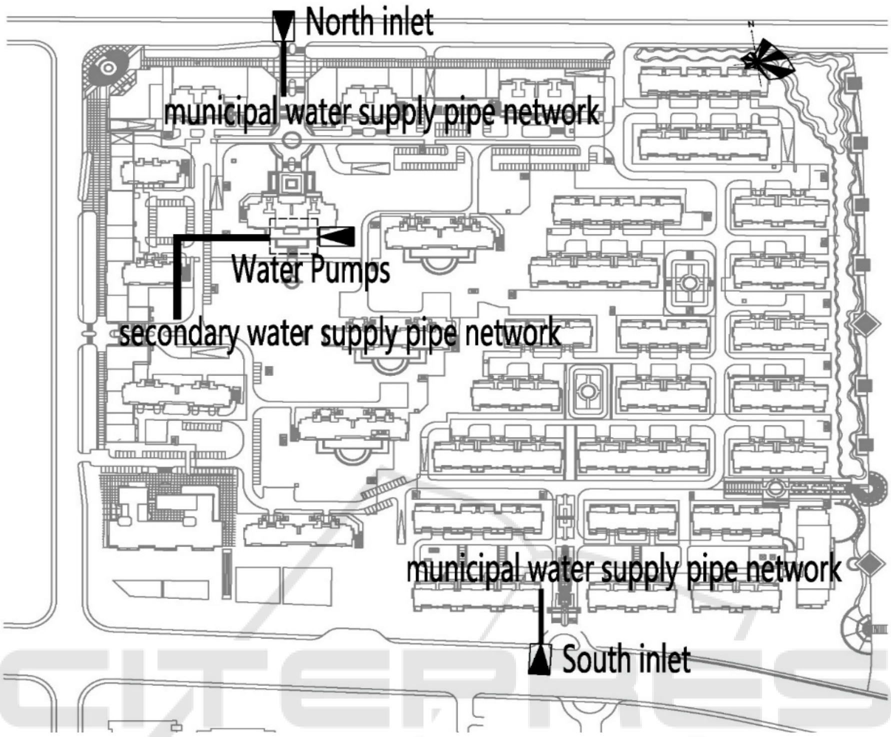

Figure 2: The DMA schematic.

With a small number of convenience stores scattered throughout the DMA, more than 95% of consumption unit of tap water is residential; in which 1,030 households are supplied by municipal water supply pipe network and 1730 households by secondary water supply pipe network. Hourly statistics and short-time inference were used simultaneously and MNF observation time was selected from 00:00 to 6:00 every day in reference to industry experience (Adlan et al. 2013; Li, Gao and Qiao 2017). Moreover, 15 minute records were multiplied by 4 to convert to hourly record for unified units and convenient comparison.

2.2 Data Collections

Figure 3 illustrated the MNF monitoring of municipal water supply pipe network. 15min record showed flow greater than zero for a long time and hour record was greater than local empirical value (Changzhou's empirical value in summer was roughly 3m^3/h) from August 18 to August 26. Hence, in the evening of August 25, noise leak detector was installed. Two leaks were detected on the 26th and repaired by the evening on the 26th. No new leak was detected from August 27 to September 5, and 15 minute record immediately dropped to 0. However hour record was fluctuating and in some cases, still greater than the local empirical value; although its extreme values were lower than before the repair, and the general trend was lower (there will be further analysis for the fluctuations after September 6 later).

Figure 4 illustrated the MNF monitoring of the secondary water supply pipe network, with the same monitoring and leak detection methods as the municipal network. Leaks were detected on August 19 and repaired on August 20. No new leak was detected from August 21 to September 13. 15 minute records immediately dropped to 0, but with intermittent fluctuation and a peak value of 4. While the MNF's hour records were also lower than before repair, they were still greater than the local empirical value in some cases with the same intermittent fluctuation.

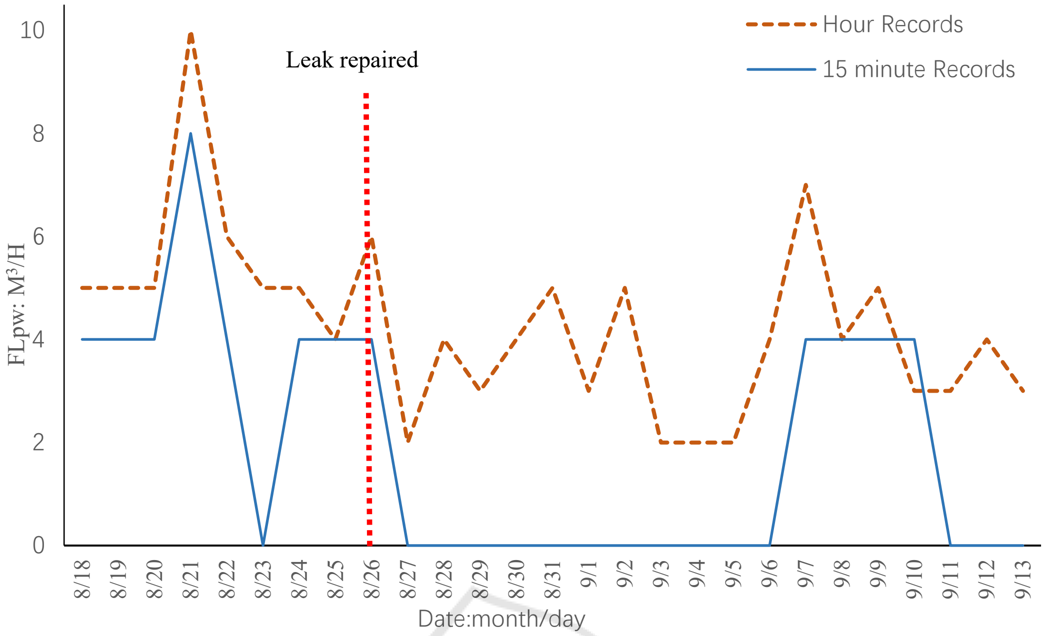

Figure 3: MNF records in municipal water supply pipe network.

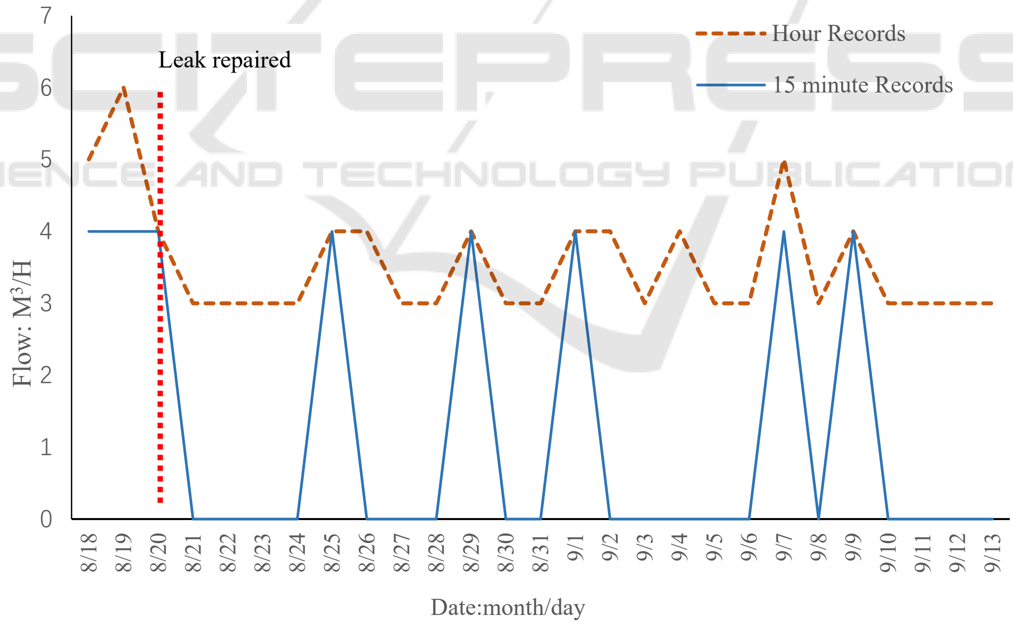

Figure 4: MNF records in secondary water supply pipe network.

2.3 Interpretation of Results

Based on the above analysis, it is easier to determine whether a leakage existed by 15 minute record than hourly record because 15 minute records can better shield the influence of the customer's normal night-time water consumption when MNF is being recorded. However, it is still necessary to conduct a detailed analysis regarding the intermittent fluctuation of 15 minute record and why the hourly records after leak repaired were still greater than the local empirical value.

3 DISCUSSION

3.1 Accuracy Analysis on 15min Record

3.1.1 Accuracy Impact of Data Recording Equipment

The unit measurement of metering equipment for water supply pipe networks can reach per liter or higher precision. However, in present day China, the data recording equipment precision for metering is in cubic meters in most water supply systems, which means the collected flow value less than 1 m³ cannot be recorded and will show a rounded value. As a result, when the flow value collected by metering equipment is less than 0.5 m³ per 15 minutes, the equipment will record the data at value 0 m³; if the flow value is greater than 0.5 m³ but less than 1 m³ per 15 minutes, the equipment will record the data at value 1 m³. The MNF's 15 minutes records in Fig.3 and Fig.4 were the minimum value collected per 15 minutes every night, of which the time interval was between 20-25 hours, so the customer's normal night-time water consumption was close to zero. In addition, since the pipes in this DMA was relatively new, there was less background leakage. Therefore, the MNF's 15 minute records after leaks were repaired should be less than 1 m³/15min and might float around 0.5 m³/15min which meant the value alternately appeared to be greater than 0.5 and less than 0.5 due to the progressive counting. On account of accuracy, the value collected above couldalternate between 0 m³ and 1 m³ after being fed back to the recording equipment, and alternate between 0 m³ and 4 m³ after being converted to hourly record as shown in Fig.3 and Fig.4.

The same situation could be verified by the continuous MNF's 15 minute records of the secondary water supply pipe network for a period of time in a day. As shown in Fig.5, the solid blue line represent the change trend of the actual 15 minute records while the dotted orange line represent the converted hour record which showed greater value fluctuation.

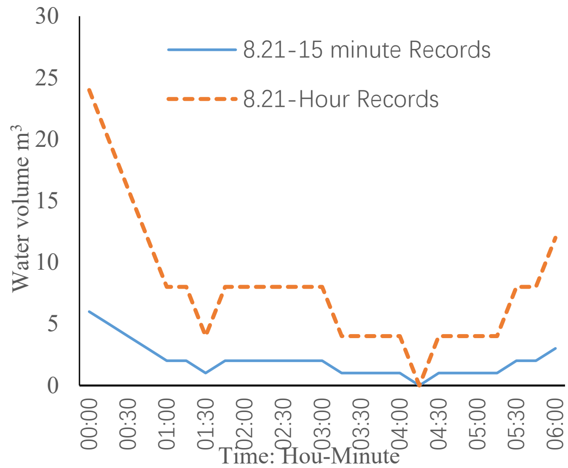

Figure 5: 15 minute records and calculated value from 0:00 to 6:00 on 21 August in secondary water supply pipe network.

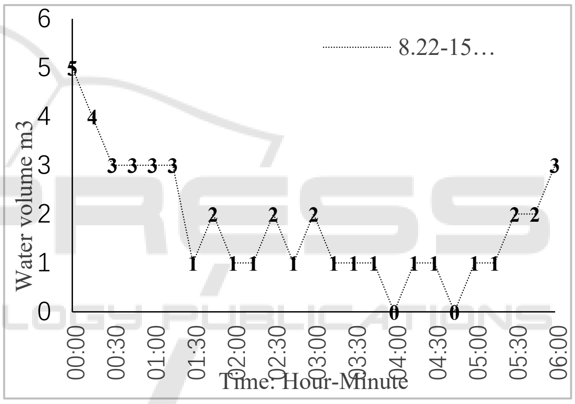

Figure 6: 15 minute records from 0:00 to 6:00 on 22 August in secondary water supply pipe network.

In addition, low precision of recording equipment destroys the smoothness of the data curve which was represented in the form of broken lines, as shown in Fig.6.

3.1.2 The Ratio Impact Between Instantaneous Flow and Meters' Diameter

It could be seen from Fig.3 and Fig.4 that the alternation frequency of 0 and 4 in secondary water supply pipe network was significantly more than in the municipal water supply pipe network after leaks were repaired. For example, after the leak was repaired in the municipal water supply pipe network and the 15 minute record dropped to 0 m³ on August 26, there was an interval of 10 days until the next fluctuation occurred on September 6. However, in secondary water supply pipe network, after the repair on August 20, the next fluctuation occurred on August 24, only 4 days apart. Moreover, as many as five fluctuations occurred between August 20 to September 13, and the shortest interval was less than one day.

The reason for such difference could be attributed to the deviation of the matching degree (symbolized by Ma) between the minimum flow and the diameter (Guo and Lin 2019; Zheng 2016) of metering equipment in the DMA's inlets. For research purposes, the Ma value could be translated into the ratio between the number of households and the diameter of DMA pipe network inlets, as shown in Table 1.

The calculation of Ma value in Table 1 was based on the premise of meeting the basic water needs in the DMA. It could be seen from Table 1 that the Ma value of municipal water supply pipe network was much smaller than that of secondary supply pipe network, indicating that the redundancy of inlet diameter of municipal supply pipe network was greater because it must be responsible for outdoor fire hydrant water supply. However, as the main water consumption within DMA came from households, a greater Ma value showed larger domestic water consumption which could be evidenced by the fact that the continuous 15 minute records of the secondary supply over a period of time were generally greater than those of the municipal supply as shown in Fig.7.

Although the measurement accuracy of mechanical water meters have been greatly improved with technological progress, their measurement accuracy for small flow rate will decrease correlating with the increase of inlet diameter to flow rate ratio (Zhang et al. 2020; Yuan Da and Chen 2019), which can also be considered that the lower Ma value leads to increase in MNF measurement error. The specific reflection in this research was that the two DN200 water meters with lower Ma value at the inlet of municipal water supply pipe network might miss meter or meter less during low flow rate, which leaded to increased recording of flow lower than 0.5m^3/15min and cost long time to accumulate to the records greater than

Table 1: Calculation of the Ma value.

Supply pipe network	Households(H)	Pipe inlet Diameter (D)	Number(N)	Ma=H/(D×N)
Municipal water	1030	DN200	2	2.575
Secondary water	1730	DN150	1	11.533

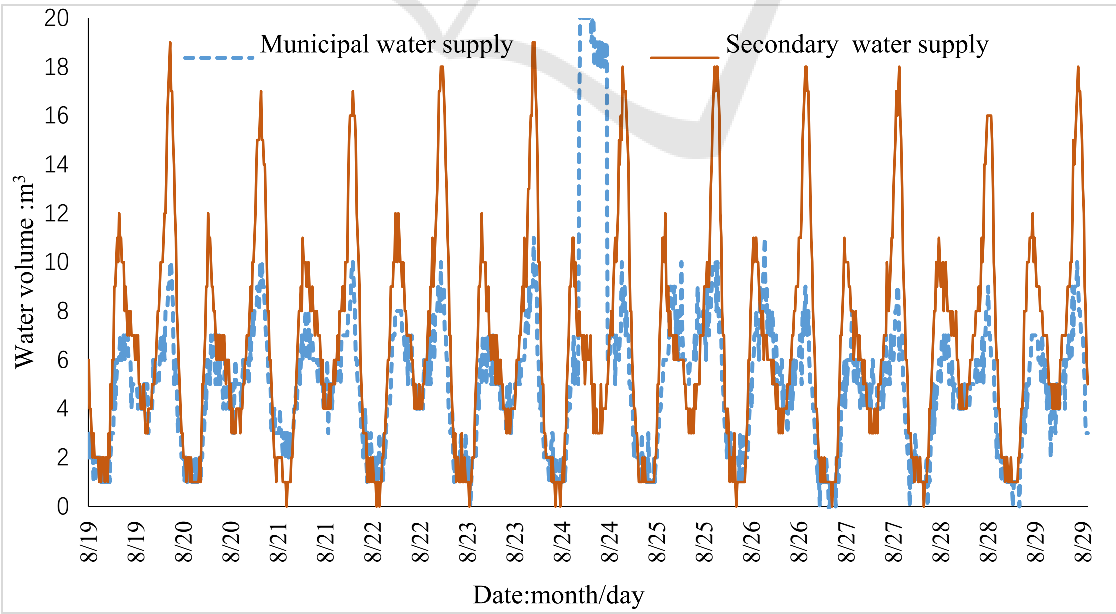

Figure 7: 15 minute frequency pipeline flow monitoring.

$0.5m^3/15min$. Meanwhile, the only one DN150 water meter with much higher Ma value at the inlet of secondary water supply pipe network could meter low flow rate precisely, which made shorter time to accumulate to the case greater than $0.5m^3/15min$. As a result, the situation shown in Fig.3 and Fig.4 appeared, Fig.7 also provided the same evidence as more alternations between 0 and peak value of MNF's 15 minute records appeared in the secondary water supply pipe network. Considering that most water meters with diameters of 200 and below are mechanical, this measurement error should be paid attention to.

3.1.3 The Mutation Impact Caused by Flow Change

The above discussion explained why there were intermittent fluctuations of MNF records in DMA water supply network after leaks were repaired, but it doesn't explain the continuous peak value of the 15 minute records from September 7 to September 10 shown in Fig.3; other operations involving the flow changes need to be further considered (Arregui et al. 2006).

In order to further verify the low Ma value's impact on the measurement in municipal water supply pipe network, the DMA's north inlet was shut off on September 6, all municipal water flowed in from the south inlet, causing the Ma value to double. As shown in Fig.3, both 15 minute and hour records of MNF increased significantly on September 7 and lasted for about three days, after which all records returned to a normal steady state. This test indicated that flow mutation had a greater and longer impact than Ma value on measurement accuracy.

3.2 Influencing Factors and Application Status of MNF Evaluation Mechanism

Based on the above discussion, it is easy to conclude the main factors influencing MNF's application in leakage assessment:

(1) Interference between the measuring frequency and customers' normal night-time water consumption.

Relevant experiments show that the measurement frequency of pipeline flow is inversely proportional to the interference from the customer's normal night-time water consumption, that is, higher the measurement frequency, lesser the interference, sometimes even negligible.

(2) The measuring precision of metering equipment and recording precision of data equipment.

These two kinds of precision can limit the previous factor as it is impossible to accurately determine the leak existence by short-time inference with higher measuring frequency if any equipment's precision fell short. This factor is the biggest shortcoming in promoting widespread short-time inference leak detection. For water supply enterprises in most Chinese cities, the smallest measuring unit of metering equipment is in cubic meters and the recording precision of data equipment is per hour, rarely the per 15 minutes needed.

Taking the MNF record of the municipal water supply network in this DMA experiment as an example, limited to the low recording precision of data equipment and small Ma value of pipe network inlet, 0 value also appeared in the 15 minute records at the leak judgment stage which affected the accuracy of leak determination, though the value lasted for a short time and were different from that after leak repaired. Therefore, if 15 minute records changed to per 5 minutes, it can be speculated that more 0 value records will continue to appear and interfere with the accuracy of leak detection.

(3) Pipeline state and background leakage.

This factor's interference is relatively easy to be evaluated compared with the above two. Benefited from the popularization and widespread application of geographic Information System (GIS) in China's water distribution system as well as large-scale pipeline more standardized renewal and construction, the basic physical information of supply pipelines can be gained easily and the source ledger can be traced. Based on above, the water supply networks with the same pipeline attributes in a DMA can be classified and recorded in order to a relatively accurate assessment of the background leakage, reducing the influence due to differences in pipeline conditions.

(4) Compound judgment criteria for leakage determination.

Table 2: The MNF of leak repaired DMAs.

DMA's Name	MNF (Hour Record) (m^3/hour)	Households (H)	Consumption per Household (L/hour)	Pipe inlet Diameter(D)	Number	Ma= H/(D×N)
DMA-1	0	215	0	DN150	2	0.72
DMA-2	0	164	0	DN150	2	0.55
DMA-3	1	1910	0.524	DN200	2	4.78
DMA-4	1	377	2.653	DN100	1	3.77
DMA-5	3	1110	2.703	DN150	1	7.40
DMA-6	4	1413	2.831	DN200	2	3.53
DMA-7	5	1740	2.874	DN200	1	8.70
DMA-8	5	1679	2.978	DN200	2	4.20
DMA-9	5	1841	2.716	DN200	2	4.60
DMA-10	1	534	1.873	DN150	2	1.78

In the actual application process of MNF for leakage determination, hourly statistics may be more tolerant to low precision metering equipment and low Ma value. Taking 10 DMAs with hourly statistics for leak determination as an example in Changzhou, China, in which most buildings are residential and pipeline state are almost same with no leak could be detected, the monitoring and statistical data for July-August were shown in Table 2 with an accuracy of 1 m^3.

The following content can be drawn from the table:

① Based on the stability data from DMA-3 to DMA-9, it could be calculated that the customer's normal night-time water consumption in the same type DMA was about 2.6L/Hour to 2.9L/Hour in summer for MNF.

② The reason why the MNF values in DMA-1 and DMA-2 were zero could be speculated that the Ma value is too low to precisely meter the small low, and the same reason for low MNF value in DMA-10. Through investigation, the reason for DMA-3's low MNF was determined to be caused by low occupancy rate in the area.

③ The acceptable MNF can be calculated by hourly statistics when Ma value is greater than 4, that further proof hourly statistics' tolerance is stronger than short-time inference's for low Ma.

4 CONCLUSION AND SUGGESTION

In the actual application process of MNF for leakage determination, short-time inference can provide information quickly and concisely, but need higher precision equipment to do so. As equipment get continuously renewed and upgraded, leak detection using short-time inference will become more widespread.

Short-time inference is the trend of MNF for leakage determination, upgrading China's water supply enterprises' equipment will take a long process, and the equipment should match with the leak control requirements and the improvement of leak detecting technology for water distribution in China. Combined with the existing facility conditions, there are roughly three following suggestions for leak control at the current stage:

(1) Through sorting out the impeccable GIS information of water distribution system, accurate pipeline attributes can be gained so that reasonable background leakage can be assessed.

(2) With complete DMAs' user and consuming information, the matching degree (Ma) between the minimum flow and the diameter of metering equipment in the DMA's inlets can be accurately calculated. On this basis, for residential-based DMAs, Ma value should be improved, and small-caliber non-residential meters shouldn't be

greater than 15%. Industrial and commercial water meter with diameter over DN40 are not recommended to be included in residential-based DMA.

(3) For new DMA or newly installed water meters, high-precision metering equipment and high-precision data recording system should be applied immediately in order to promote the popularization of MNF's short-time inference for more convenient leak determination.

DATA AVAILABILITY STATEMENT

The research presented in this paper was part of the daily work content of pipeline leakage control in Changzhou CGE Water Co., LTD. All the data came from daily monitoring work which all authors participated in.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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