

## Optimal Control for Water Loss from Water Distribution Network: A Case Study of Beijing

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### ABSTRACT

*Water loss control is a key issue for most water supply companies all over the world because of freshwater scarcity and ever-rising water demand. Beijing is one of the cities facing severe water scarcity, so water loss control has been emphasized during the past decades. However, due to the huge size of the water distribution network, there is a great need to optimize the water loss control strategies. The water distribution network of Beijing has been planned to be partitioned into over 700 DMAs. Assessment of the DMAs' water loss conditions and prediction of the achievements of different water loss control measures are critical to manage these DMAs. The goal of this paper is to develop a mathematical model to reveal how low the water loss of a DMA could go, so as to optimize the water loss control strategies. 36 DMAs were selected as study areas and data of the lowest minimal night flow (LMNF) and DMA characters (including pipe material, pipe length, number of properties, pipe age, and water pressure) were collected. The relationship between LMNF and DMA characters was established using multi-variant regression method. The model fit the data with  $R^2=0.8$ . The model was then compared to the commonly used water loss indicator UARL and its sensitivity to the input variables was analyzed. Finally, the model was applied by Beijing Waterworks Group to optimize its water loss control strategies.*

**Keywords:** Optimal water loss control, Water distribution network, Lowest minimal night flow (LMNF) model.

## 1 BACKGROUND

Water loss from water distribution network has been a serious problem for most water industries around the world. As the biggest developing country in the world, China is experiencing rapid urbanization, which incurs rising water demand. In the meantime, China is short of freshwater. The amount of China's freshwater resources per capita is less than one fourth of the world average. Therefore, there is a great need to reduce the water loss from water distribution network, which accounts for about 18 percent of the water supplied all over the country.

During the past decades, China's water supply companies have paid much attention to control the water loss. Several measures, e.g. active leakage detection, pipe replacement and pressure management, were taken to reduce water loss and some achievements were obtained. Beijing is one of the cities making efforts to water loss control. However, because the pipe network is very large, a smarter way is needed to improve the water loss control efficiency. Partitioning the pipe network into smaller sub-networks, known as district metered areas (DMAs), is well recognized as an effective way to improve water loss control efficiency. In this way, water loss of a whole system can be broken down into many smaller areas so that areas in worse conditions can be identified and accordingly higher priorities can be assigned.

Many index can be used to assess the water loss conditions of DMAs, among which infrastructure leakage index (*ILI*) is proved to be suitable for comparisons between pipe networks with different characteristics [1]. *ILI* is the ratio of current annual real losses (*CARL*) to the unavoidable annual real losses (*UARL*), where *UARL* can be calculated with the properties of a given pipe network. The variables contain length of mains, length of private pipes, number of service connections, and water pressure. *ILI* has been applied in many water supply systems to assess their conditions.

However, when applying *ILI* in China, two major difficulties emerged. One is in the determination of *CARL*. Usually, water balance analysis is needed to determine *CARL*. However, due to poor data quality it is difficult to conduct an accurate water balance analysis to know the real losses for most water supply companies in China. The other difficulty exists in the calculation of *UARL*. China’s water supply pipe networks are quite different from the networks based on which the concept and method of *UARL* were proposed. The length of water mains and length of private pipes are difficult to discern because most people live in apartments and the consumed water is metered in each apartment.

Beijing has one of most complex water supply pipe networks in China. The total pipe length is more than 10,000 km and 2.7 million of water is supplied per day. The network has been planned to partition into DMAs since more than 10 years ago. 792 DMAs were planned, of which 485 had been created by the end of 2016. In order to improve the water loss control efficiency, it is important to manage these DMAs in a smarter way.

This study investigated the DMAs’ properties and the lowest minimal night flow (*LMNF*) that can be achieved using the current technologies. Then the relationship between *LMNF* and DMA properties were established using nonlinear multivariate regression method. Finally, the relationship was applied in all the DMAs to evaluate their water loss conditions and optimize the water loss control strategies.

## 2 MATERIALS AND METHOD

### 2.1 Study Areas and Data Collection

36 DMAs, 21 of which were from Beijing with the remaining from 3 other cities, were selected as the study areas. These DMAs have different properties as shown in Table 1. Flow and water pressure at the DMAs inlets were monitored and recorded every 15 minutes. Leaks in these DMAs were intensively detected and fixed until no more leaks could be found with the current technologies so that the minimal night flow (MNF) in this situation could be the *LMNF*.

Pipe length, pipe material, number of properties, and pipe age of the DMAs were calculated. In this study the average MNF of a 2-week period after the leakage detection was used as *LMNF* to reduce the influence of the normal night water use. These data were used to develop the *LMNF* model.

Table 1. Basic Information of the Experimental DMAs

Properties	Value
Pipe length (km)	1.33~12.6
Pipe materials	Cast iron, ductile cast iron, stainless steel, plastic, etc.
Pipe age (yr)	1~33

Number of properties	64~7364
Night inlet pressure (m)	23.4~69.3
<i>LMNF</i> (L s <sup>-1</sup> )	0.18~17.3

## 2.2 Method of the *LMNF* Model Development

Table 1 lists the information of the DMAs. The essence of the *LMNF* model is to establish the relationship between *LMNF* and the properties of the DMAs. The dependent variable is *LMNF* and the independent variables are length of cast iron pipes ( $L_{CI}$ ), length of non-cast-iron pipes ( $L_{NCI}$ ), number of properties ( $N_p$ ), length weighted average pipe age ( $A$ ), and average inlet water pressure during 2:00-5:00 am ( $P$ ).

Multi-variant regression method was applied to establish the model. The structure of the model was shown as Equation (1).

$$LMNF=(a_1L_{CI}+a_2L_{NCI}+a_3N_p) \cdot A^b \cdot P^c \quad (1)$$

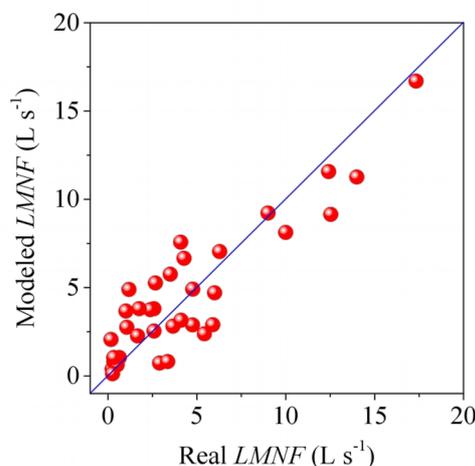
Where, the dimensions of *LMNF*,  $L_{CI}$ ,  $L_{NCI}$ ,  $N_p$ ,  $A$  and  $P$  are L s<sup>-1</sup>, km, km, 10<sup>3</sup> properties, and m, respectively;  $a_1$ ,  $a_2$ ,  $a_3$ ,  $b$  and  $c$  are parameters to be calibrated. In this study, the parameters were calibrated using Levenberg-Marquardt algorithm which was frequently used to solve nonlinear least squares problems.

## 3 RESULTS AND DISCUSSIONS

### 3.1 The *LMNF* Model

Data of the 36 DMAs were used to calibrate the parameters of Equation (1). The obtained model is shown as Equation (2). The model fits the data well with  $R^2=0.80$ . Figure 1 compares the modeled and real *LMNFs* of the DMAs. It can be seen that the data plots evenly distributes around the diagonal  $Y=X$ , which indicates the model is a good fit of the data.

$$LMNF=(0.00041L_{CI}+0.00014L_{NCI}+0.0015N_p) \cdot A^{0.72} \cdot P^{1.4} \quad (2)$$



*Figure 1. Comparison between the Modeled and Real LMNFs of the DMAs*

From Equations (1) and (2), *LMNF* has a linear relationship with pipe length ( $L_{CI}$  and  $L_{NCl}$ ). The reason is that it is assumed that pipe breaks linearly distribute on pipes. The longer is the pipe, the more are the breaks and consequently more water runs out through the breaks. The relationship between *LMNF* and number of properties ( $N_p$ ) is also linear. It is because, on one hand, the mathematical expectation of normal night water use that was contained in the *LMNF* is linearly related to the number of water users; on the other hand, leaks in the user pipes can also be assumed to be linearly related to the number of water users.

However, from Equation (2), the relationships between *LMNF* and pipe age ( $A$ ) and water pressure ( $P$ ) are nonlinear. It indicates that the influences of pipe age and water pressure on *LMNF* are more complex than pipe length and number of properties. Old pipes are more prone to fail but the possibility is not necessarily linearly related to pipe age. It has been reported much in the literature [2-5]. Water pressure has been demonstrated to influence leaks in an exponential manner with the exponent of zone-average pressure usually being from 0.5 to 2.5 [6]. In this study, the exponent is 1.4. Because *LMNF* contains a proportion of normal night water use, which is not pressure-dependent, the exponent tends to be underestimated. If only leaks are considered, the obtained exponent would be larger than 1.4.

It should be noted that with data of more and more DMAs being available in the future, more accurate models can be developed. For example, pipes can be grouped into more fine categories according to their materials, which would reveal the difference among non-cast-iron pipes. Not only the parameters but also the model structure could be different.

### 3.2 Comparison between the *LMNF* Model and the *UARL* Model

The concept and methodology of *UARL* was proposed in the late 1990s. It describes the lowest value of real losses that can be achieved at the current operating pressures if there were no financial or economic constraints [1]. *UARL* ( $L d^{-1}$ ) can be calculated by Equation (3).

$$UARL=(18L_m+0.8N_c+25L_p) \cdot P \quad (3)$$

Where,  $L_m$  is mains length (km),  $N_c$  is number of service connections,  $L_p$  is the total length of private pipe (underground pipe between the edge of the street and customer meters) (km), and  $P$  is average operating pressure (m).

*UARL* proves to be a good performance indicator to describe how low the real water losses could be if the water supply system is in good condition and well-managed. It has been used to calculate *ILI* by many water utilities to assess their network's water loss conditions during the past years [7, 8].

The differences between *LMNF* and *UARL* mainly exist in the following aspects:

- *LMNF* calculates the lowest minimal night flow of DMAs with different conditions while *UARL* calculates the real water losses. *LMNF* contains a proportion of normal night water use.
- *UARL* is applicable for DMAs, systems, cities or even countries while *LMNF* is applicable for only DMAs.
- *LMNF* discerns pipes by materials while *UARL* by the ownership of the pipes.
- *LMNF* takes into account pipe age while *UARL* not.

- *LMNF* uses number of properties while *UARL* uses number of service connections. For real losses, number of service connections is more applicable and for minimal night flow number of properties is more applicable.
- The parameters of the *LMNF* model were obtained through calibration while those of the *UARL* model were the statistical data from practice of water loss control.

From the differences between the two indicators, the main advantage of *UARL* is that it provides a benchmark for water utilities to know how low the real water losses could be if their pipe networks are in good conditions and well-managed. However, it cannot give suggestion on how the real losses can get to that value. The main advantage of *LMNF* is that it takes into account pipe material and pipe age; therefore, it could provide suggestion on water loss strategies. For example, *LMNF* model can give how *LMNF* would be if pipe materials are changed or if old pipes are replaced with new ones so that water loss control strategies can be optimized.

### 3.3 Sensitivity Analysis of the *LMNF* Model

Sensitivity analysis is important to understand the impact of the inputs on the output for a model. Usually, it can be performed by investigating the responses of the output to the changes of the inputs within a range. In this study, the responses of *LMNF* to the changes of the independent variables, i.e.  $L_{CI}$ ,  $L_{NCI}$ ,  $N_P$ ,  $A$  and  $P$ , was investigated by changing the independent variables by from -50% to 50% with an interval of 5%. When one variable was changed, the others were kept at their averages. Table 2 gives the averages and the changing ranges of the independent variables. The calculated *LMNF*, with all the independent variables at their averages, was 4.62 L s<sup>-1</sup>, which was used as a benchmark to see the *LMNF* changes with changing independent variables.

Table 2. Averages and Changing Ranges of the Independent Variables of the *LMNF* Model

Independent variables	Averages	Changing ranges
$L_{CI}$ (km)	1.69	[0.85, 2.54]
$L_{NCI}$ (km)	2.14	[1.07, 3.21]
$N_P$ (10 <sup>3</sup> properties)	2.02	[1.01, 3.03]
$A$ (yr)	16.2	[8.10, 24.3]
$P$ (m)	36.6	[18.3, 54.9]

Figure 2 shows the *LMNF* responses to the changes of independent variables. It depicts that *LMNF* was most sensitive to water pressure  $P$  and least sensitive to length of non-cast-iron pipes. It implies that pressure management is the most effective way to control water loss. The model’s sensitivity to number of properties and pipe age was similar and next to water pressure. The reason why the model is sensitive to number of properties is probably that *LMNF* contains some normal night water use which is dependent on the number of water users. The model’s sensitiveness to pipe age indicates that pipe replacement is also an effective way to reduce water loss.

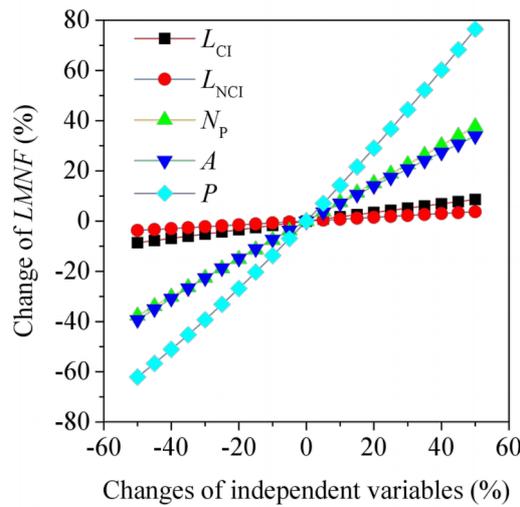


Figure 2. Sensitivity of LMNF Model to the Input Variables

### 3.4 Optimization of Water Loss Control Strategies for DMAs

LMNF model can calculate the lowest minimal night flow for DMAs with specific conditions. What’s more, if the DMAs conditions change (usually due to active water loss control measures), new LMNF value will be obtained. Comparing the calculated LMNF and the current MNF (CMNF), the water savings could be easily obtained and consequently cost-benefit analysis could be performed to optimize the water loss control strategies.

This study considers two water loss control measures: active leak detection and water pressure management. Because LMNF model was derived from the data of DMAs that were intensively leak-detected, subtracting CMNF of a DMA by the calculated LMNF with the current operating conditions would obtain the benefits of active leak detection. If water pressure control is an option to reduce water loss, the target water pressure ( $P_0$ ) can be applied to Equation (2) to obtain the LMNF under the target pressure. Again, comparing LMNF with CMNF, it can be determined whether water pressure control is cost-effective.

Table 3 lists three DMAs to illustrate how the LMNF model was applied to optimize the water loss control strategies. If the investment of a water loss control measure could be paid back within a period pre-determined by a water utility, the measure is decided to be cost-effective. In this study, the pre-determined payback period is 1 year. The costs of leak detection and water pressure reduction for each DMA are assumed to 10,000 RMB and 100,000 RMB, respectively (RMB is the unit of Chinese currency). The cost of water is assumed to be 5 RMB/m<sup>3</sup>.

According to Table 3, water savings through different water loss control measures were calculated and the measures were suggested for the three DMAs. Actually, more DMAs have been analyzed for Beijing water distribution network. It is supposed that the model will be used to assess all the 792 DMAs and give suggestive water loss control measures for them in the future.

Table 3. Examples of Water Loss Control Optimization Using the LMNF Model

DMA properties	DMA 1	DMA 2	DMA 3
$L_{CI}$ (km)	3.89	3.50	0
$L_{NCI}$ (km)	0	1.07	12.8

$N_p$ ( $10^3$ properties)	4.07	1.38	5.60
$A$ (yr)	23.0	10.2	6.00
$P$ (m)	30.0	28.0	40.7
$P_o$ (m)	26.0	26.0	26.0
$LMNF$ under $P$ ( $LMNF_p$ ) ( $L s^{-1}$ )	8.62	2.07	6.63
$LMNF$ under $P_o$ ( $LMNF_{p_o}$ ) ( $L s^{-1}$ )	7.04	1.86	3.55
$CMNF$ ( $L s^{-1}$ )	12.5	5.90	6.65
WS through LD* ( $CMNF-LMNF_p$ ) ( $L s^{-1}$ )	3.88	3.83	0.02
WS through PR** ( $LMNF_p-LMNF_{p_o}$ ) ( $L s^{-1}$ )	1.58	0.21	3.08
WS through LD and PR ( $CMNF-LMNF_{p_o}$ ) ( $L s^{-1}$ )	5.46	4.04	3.10
Optimized water loss control strategy	LD+PR	LD	PR

\*WS: water savings; LD: leak detection. \*\*PR: pressure reduction.

## 4 CONCLUSIONS

Partitioning a pipe network into DMAs proves to be an effective way to manage water loss. However, as more and more DMAs are created, there is a great need of a method to assess the DMAs' water loss conditions and to optimize the water loss control measures. This study focused on developing a mathematical model to predict how low the minimal night flow could be under different operating conditions. Data of 36 DMAs were collected and used to develop the model. The model reveals a linear relationship between  $LMNF$  and pipe length and number of properties while a nonlinear relationship between  $LMNF$  and pipe age and water pressure. The model has a good performance to fit the data with  $R^2=0.8$ . With the help of the model, water savings of DMAs with different water loss control measures were obtained, and by comparing benefits with the costs, the optimal measures were determined.

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