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TARGET RESILIENCE INDEX FOR WATER DISTRIBUTION NETWORKS

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ABSTRACT: Urban water distribution networks (WDNs) require reliability to provide adequate pressure and good water quality. One way to assess WDNs' reliability is through a resilience index. Typically, a resilience index is an index of how the surplus of the required variables such as energy or chlorine mass compares to a system input of such variables. In this paper, we modified the resilience index to include a target value of pressure (Target Hydraulic Resilience Index, THRI) and free residual chlorine concentration (Target Chlorine Resilience Index, TCRI). We applied the THRI and TCRI to a district metering area. The results showed that both RIs clearly explain the state of the reliability of the WDNs compared to the target values. The impact of water loss on each RI is that less water loss resulted in a higher THRI while less water loss gave a lower TCRI. The THRI and TCRI can also be presented in both time and space. Hence, we can assess the deficits of temporal and spatial resilience indices from the targets. Therefore, they can be used for pressure and chlorine management to improve the WDNs' reliability.

Keywords: Resilience index, Water distribution networks, Free residual chlorine, Reliability

1. INTRODUCTION

Performance evaluation of water distribution networks (WDNs) is crucial for establishing the reliability of WDNs. One of the key performances of the WDNs is resilience. Resilience refers to the ability of the WDN to supply water with standard quality, sufficient quantity, and within the appropriate pressure range for consumers under normal and abnormal operating conditions. Gunawan I. Schultmann F. Zarghami S.A. [1] proposed two metrics for evaluating WDN performance, structural metrics, and hydraulic metrics. Water quality metric was introduced by [2] but they did not evaluate this metric.

Todini [3] proposed a strong concept of hydraulic resilience index that measures the hydraulic capacity of the WDN to cope with failures, which is indirectly related to system reliability. This resilience index has further adjusted and combined with other indices to assess network reliability [4]-[7]. However, this resilience index is focused on the existing system's resilience or reliability. Hence, we modified Todini's resilience index by substituting input power with a target value for operational purposes.

Water quality metric has been evaluated based on water quality values before and after the failures [2], [8]. As chlorine is one of the most used residual disinfection chemicals for controlling water quality in the WDNs [9], we modified Todini's resilience index for the water quality metric using free residual chlorine mass as the indicator. We then explored variations of both hydraulic and water quality resilience indices on both time and space. We also investigated the impact of water losses on the indices.

2. RESEARCH SIGNIFICANCE

The resilience of WDNs is a general evaluation of the robustness of the networks. Typically, the resilience index of the network is an index of how the surplus of the required variables compares to a system input of such variables. In this paper, we modified the resilience index to include a target value of pressure (Target Hydraulic Resilience Index, THRI) and free residual chlorine concentration (Target Chlorine Resilience Index, TCRI). By including the targets, both THRI and TCRI can assess the deficit of an existing network pressure and chlorine conditions to the target values. The temporal and spatial distribution of both indices were performed and investigated for the benefit of pressure and chlorine management. The impacts of water loss reduction on the indices were analyzed. Both THRI and TCRI can be used to identify pressure and chlorine concentration problems in both time and space. The application of THRI and TCRI can be used for pressure and chlorine management.

3. MATERIALS AND METHODS

3.1 Study Area

The study area is one of the district metering areas (DMAs) in the Samut Prakarn branch office service area, Metropolitan Waterworks Authority (MWA), Thailand. The study area is DMA170104, as shown in Fig. 1. It is a residential area with very low pressure but a very high percentage of water losses. The characteristics of the study area are shown in table 1. MWA installed three pressure loggers on fire hydrants in the DMA during the period of the investigation. The pressure loggers are Primayer Primelog 1P, which can measure pressure ranging from 0 to 10 bar with an accuracy of ±0.1% according to the specification. MWA also measured free residual chlorine concentration at three locations using HACH pocket colorimeters II. At the inlet, there was a district meter where pressure and flow were automatically recorded.

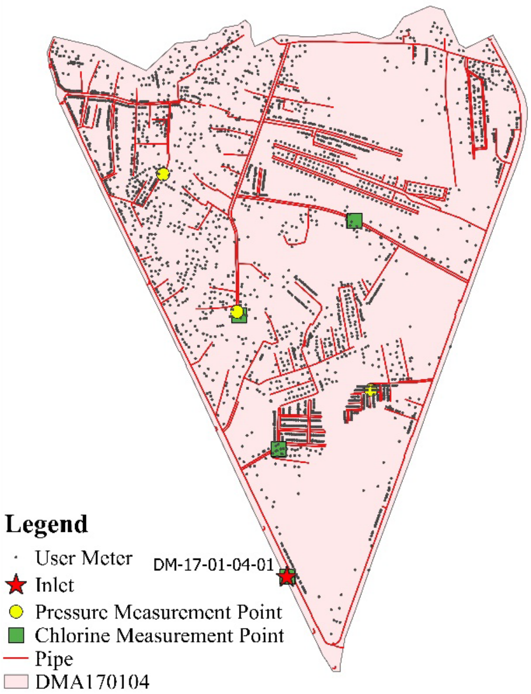

Fig. 1 DMA170104

Table 1 Main characteristics of the study area

Data	Details
Area (km^2.)	1.43
No. of customers	2,669
Total pipe length (km.)	24.61
Average pressure head (m.)	6.95
Water loss (%)	44.3

3.2 Methodology

3.2.1 Model

The EPANET model [10] was applied to simulate a water distribution network. We obtained the primary data from the MWA, such as customer meters, pipe diameters, pipe lengths, and demand patterns. Each customer type had different demand patterns and was connected to pipes using valves with no friction loss. Water loss was distributed throughout the network and simulated by the emitter function as shown in eq.1.

$$Q_{leak} = CP^{N1} \quad (1)$$

where Q_{leak} and P are the leakage flow (m^3/hr) and the pressure (m.), respectively. C is the emitter coefficient. N1 is a leakage exponent and equals 1.0 since a pressure step test [11] was conducted and N1 was found to be close to 1.0.

The free residual chlorine (FRC) is modeled using the first-order decay model in EPANET. The reaction rate (R) can be written as

$$R = k_b C_l + \frac{A}{V} k_w C_l \quad (2)$$

where C_l = FRC concentration; A/V = surface area per unit volume within pipe; k_b and k_w = bulk and wall reaction coefficients, respectively; k_b = −0.3769 hour^{-1} (taken from MWA bulk FRC test report); and k_w is used as an adjusting parameter.

The hydraulic and quality models were already calibrated by MWA. We used 1-h timestep for hydraulic simulation and 1-min timestep for water quality simulation. We simulated the model for 96-hour under a repetitive pattern of source and demand inputs so that the initial conditions did not influence the water quality results [12] and used the last 24-hr results for calculating resilience indices. There were two cases in this study: WDNs with existing (44.3%) and planned (19%) percentages of water loss conditions [13].

3.2.2 Resilience index

The resilience index (RI) by Todini [3] is the ratio of the excess power and the difference between the total available power at the entrance in WDNs and the total minimum power at user nodes. If the delivery head is more than or equal to the required or minimum head at each node, the customers will receive the desired demand. The RI can measure the reliability of WDNs when pipes fail [3]. RI can be calculated by using the following equation.

$$RI = \frac{\sum_{i=1}^{nn} Q_i (h_i - h_i^*)}{\sum_{k=1}^{nr} Q_k H_k - \sum_{i=1}^{nn} Q_i h_i^*} \quad (3)$$

where h_i and h_i* are the head (m.) and the minimum satisfied head (m.) at each node i, respectively. n_n is the number of nodes. Q_i is the demand (m^3/hr). Q_k and H_k are the discharge (m^3/hr) and the head (m.) of each reservoir k. n_k is the number of reservoirs.

3.2.3 Target hydraulic resilience index

For the low-pressure WDNs which need to

increase the pressure, the original RI in eq. (3) cannot indicate the appropriate pressure level needed to apply to improve the WDNs reliability. In this study, we modified the RI to incorporate a target pressure level as a target hydraulic resilience index (THRI) as follows.

$$THRI = \frac{\sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}P_{i,t} - \sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}P_{min}}{\sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}P_{target} - \sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}P_{min}} \quad (4)$$

where t and n are time (hr.) and the number of user meters, respectively. $Q_{i,t}$ is the satisfying demand at each node i at time t (m^3/hr). $P_{i,t}$ is the pressure at each node i at time t (m.). P_{min} is the minimum pressure (m.) defined as MWA service level of 5 m. P_{target} is the target pressure (m.) from MWA strategic plan [13] defined as 9.5 m.

3.2.3 Target chlorine resilience index

The free residual chlorine (FRC) is typically used as one of the water quality indicators in the WDNs [9]. To calculate the resilience index of FRC, we modified the resilience index using FRC mass instead of power. The target chlorine resilience index (TCRI) shows the surplus of FRC mass over the difference between the target FRC mass and the minimum FRC requirement. Hence, the TCRI can be expressed as:

$$TCRI = \frac{\sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}C_{i,t} - \sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}C_{min}}{\sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}C_{target} - \sum_{t=1}^{24}\sum_{i=1}^{n} Q_{i,t}C_{min}} \quad (5)$$

where $C_{i,t}$ is the FRC concentration (mg/L) at each node i at time t. C_{min} is the minimum FRC concentration as recommended by World Health Organization (WHO) as 0.2 mg/L [9]. C_{target} is the target FRC concentration (mg/L) which should not exceed the odor threshold value of 0.6 mg/L [14].

3.2.4 Applications of THRI and TCRI

By assessing the deficits of temporal and spatial resilience indices from the targets as THRI and TCRI, we can use them for pressure and chlorine management to improve the WDNs' reliability. The temporal THRI and TCRI can be used as the adjustment to estimate the new pressures and chlorine dosing rates at the inlet for 24 hours. From Eq. (4) and Eq. (5), we can replace the THRI or TCRI values with 1.0 and use the current THRI or TCRI to calculate the adjustment. The adjustment and new input value can be calculated by the following equations:

$$\boldsymbol{Adj_t} = (\boldsymbol{1} - \boldsymbol{RI_t}) \times (\boldsymbol{Tarv} - \boldsymbol{Mrv}) \quad (6)$$

$$\boldsymbol{New_t} = \boldsymbol{Exv_t} + \boldsymbol{Adj_t} \quad (7)$$

where Adj_t is the adjustment value at time t and RI_t is the current THRI or TCRI at time t. The *Tarv* and *Mrv* are the target pressure or target free residual chlorine concentration and the minimum pressure or minimum free residual chlorine concentration requirement, respectively. The New_t is the new input value of pressure or free residual chlorine concentration at time t and the Exv_t is the present or existing pressure or free residual chlorine concentration at time t. This adjustment process can be iterated until the pressure or chlorine concentration results are satisfying.

4. RESULTS AND DISCUSSIONS

4.1 Target Hydraulic Resilience Index Analysis

The THRI results of the whole network are 0.151 and 0.205 for WDNs with existing water loss (44.3%) and 19% of water loss, respectively. They imply that the average powers of WDNs are 15.1% and 20.5% above the minimum power requirement and 84.9% and 79.5% below the target power plan. The 0.054 (0.205-0.151) increase of the THRI from the 19% water loss case indicates that decreasing water loss can improve hydraulic system reliability. We calculated the original resilience index of the existing case to be 0.179, which only indicated that the surplus power of the system was 17.9% above the minimum requirement. The remaining 82.1% implied the ratio of energy losses to the available input power in the system. It did not state the surplus power condition compared to the target value.

The temporal distribution of THRI in Fig. 2 shows the improvement of THRI every hour when the water loss reduces to 19%. Between 11.00 to 15.00, the THRI values of the existing case are lower than 0 because the pressure at the inlet was dropped too low. It means that users will get lower pressure than the service level. By examining the temporal THRI, we can manage the system pressure to satisfy the minimum pressure requirement. We will know the exact time at which the THRI approaches the target or below the service level, so we can increase or decrease pressure.

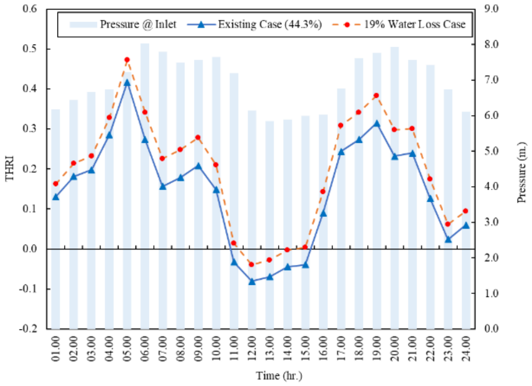

Fig. 2 Temporal THRI and pressure at the inlet

Figure 3 shows the spatial distribution of THRI. We can see that the higher THRI is mostly near the inlet and the THRI values become smaller and smaller as they are further away from the inlet. The low hydraulic reliability areas can be identified. These areas can be further investigated so that we can apply the appropriate measures to the problem areas. After reducing water loss to 19% as shown in Fig. 4, the THRI becomes better in all areas. The low hydraulic reliability areas from the existing water losses are developed into more hydraulic reliability. Therefore, reducing water loss will make the WDNs have higher THRI and reliability in both time and space.

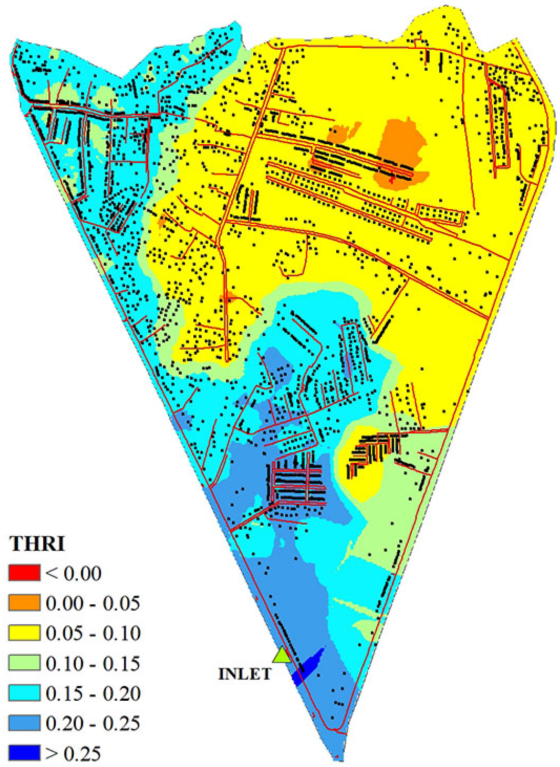

Fig. 3 Spatial THRI (Existing Case (44.3% WL))

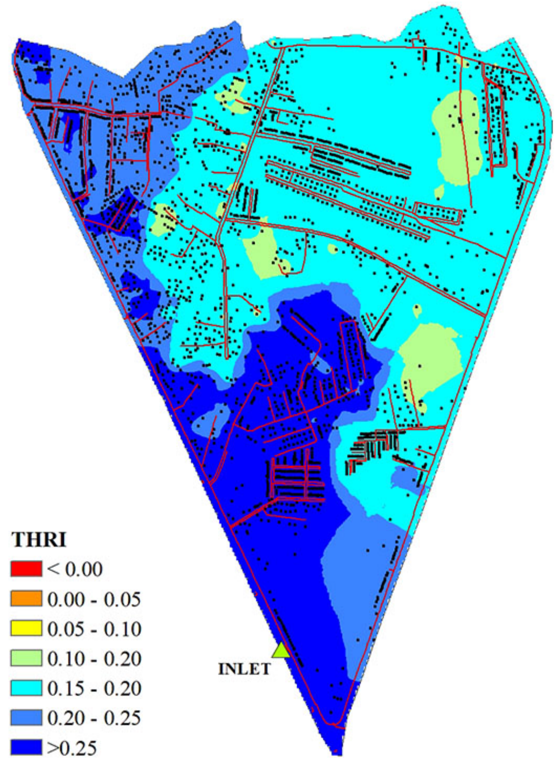

Fig. 4 Spatial THRI (19% Water Loss Case)

4.2 Target Chlorine Resilience Index Analysis

The results of TCRI of the whole network are 1.759 and 1.690 for WDNs with existing (44.3%) and 19% of water loss cases, respectively. Since the TCRI values are above 1.0, they imply that the WDN had 75.9% and 69.0% of FRC mass above the target FRC level, respectively. These values confirm users' complaints of chlorine odors. The TCRI of the water loss reduction case slightly decreases by 0.069 (3.91%). We also calculated the chlorine resilience index using the system FRC mass inputs instead of the target FRC level to be 0.652. This value only indicates that the WDN has a 65.2% FRC surplus mass of the available FRC input to the system. The 0.652 value did not identify the problem of chlorine overdoses.

The temporal distribution of TCRI in Fig. 5 shows that when water loss is reduced, the WDN has a lower TCRI. The TCRI decreases during nighttime more than daytime due to longer water ages. Since both cases of TCRIs are above 1.0 (above the target value), we can reduce chlorine input at the inlet.

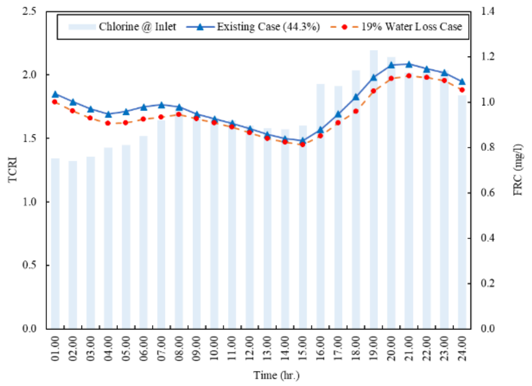

Fig. 5 Temporal TCRI and chlorine at the inlet

Figures 6 and 7 show the spatial distribution of TCRI. Figure 6 shows that almost all users have TCRI above 1.0. The water near the inlet will have an unpleasant odor and taste because the FRC concentration is considerably higher than 0.6 mg/l. Figure 7 shows that water loss reduction results in smaller TCRIs. The less water loss creates a longer water age which affects chlorine decay. Water loss reduction decreases chlorine resilience in the system, unlike the THRI where the impact of water loss reduction increases hydraulic system resilience. Therefore, the temporal and the spatial TCRI can help manage chlorine dosing rates in WDNs to improve chlorine reliability.

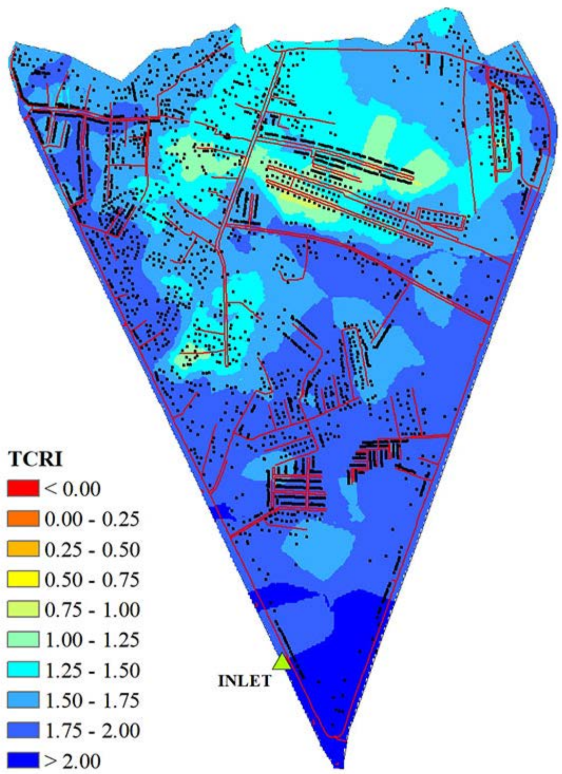

Fig. 6 Spatial TCRI (Existing Case (44.3% WL))

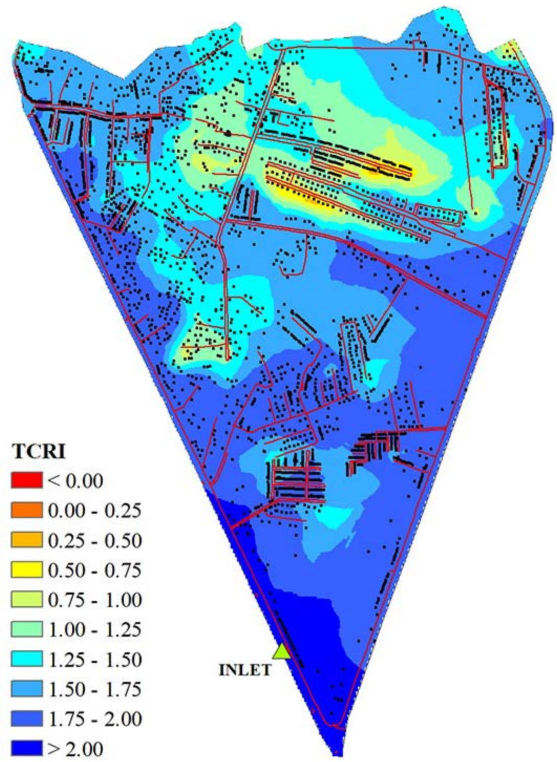

Fig. 7 Spatial TCRI of 19% Water Loss Case

4.3 Applications of THRI and TCRI

4.3.1 Pressure Management by THRI

The existing pressure pattern of the study area was low and therefore affected the THRI values. The current THRI values were even below zero at times, which means users had received pressure below the minimum pressure requirement. The current pressure inputs were between 5.8-8.0 meters, with an average pressure being 6.95 meters. After we applied the adjustments to improve the hydraulic reliability of the network, the THRI values were greatly improved. In addition, the adjustment process can be easily iterated until the THRI values of the new pressure inputs approach 1.0. In Figure 8, the THRI values become less fluctuate after each iteration, and after only three iterations, all temporal THRI values are equal to 1.0. The new pressures were between 10.5-11.7 meters, with an average pressure being 11.1 meters. The average pressure adjustment value is 4.165 meters. While the existing pressure variation was 2.2 meters, the pressure variation after adjustment was only 1.1 meters. The comparison between the current and the new pressure inputs is shown in Figure 9.

We calculated Todini's resilience index after pressure adjustment to be 0.439. It increased by 0.260 from 0.179, which was before the pressure management. The 0.260 increment value implies that the ratio of energy losses to the system energy in the network was less than before the pressure adjustment. The energy audit [15] or energy balance [16] should be performed to understand the energy balance in the network. Therefore, the pressure management by the THRI adjustment not only improves the WDN's resilience but also enhances the network efficiency.

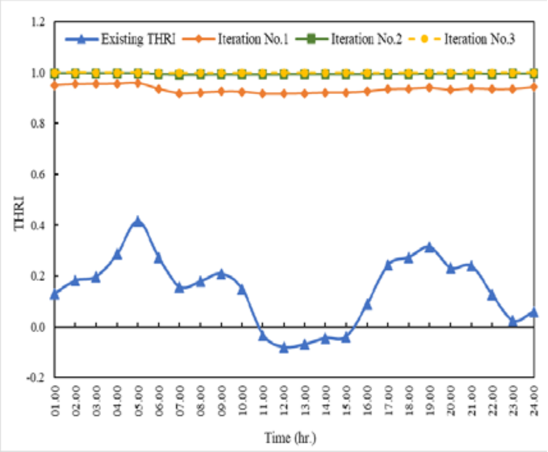

Fig. 8 Pressure management iteration process

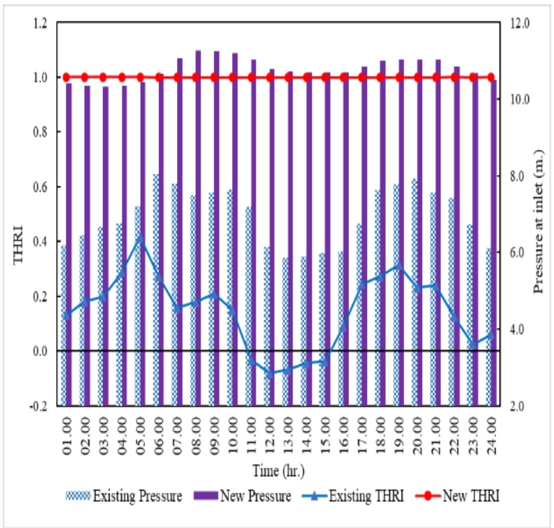

Fig. 9 THRI adjustment for pressure management

4.3.2 Chlorine Management by TCRI

From the existing case, the chlorine dosing rates were overdosed and affected the TCRI values to be greater than 1.0, which means users experienced chlorine taste and odor. The current free residual chlorine concentration at the inlet was between 0.88-1.23 mg/L, with an average being 1.03 mg/L. Therefore, we can reduce the chlorine inputs at the inlet to improve chlorine reliability in the system without jeopardizing water safety. Although the system water age affects chlorine management, we still applied the same method as pressure management.

Figure 10 shows the comparison between the existing temporal TCRI and the TCRI after adjustment. During the daytime, TCRI values are approaching 1.0. However, the TCRI values become more fluctuate during nighttime because of the effect of longer water age. In Fig. 11, the new free residual chlorine concentration at the inlet was between 0.49-0.89 mg/L, with an average of 0.69 mg/L. An average chlorine concentration drop was 0.33 mg/L. We calculated the chlorine mass input of the system by multiplying flows into the DMA with the chlorine concentrations. The existing chlorine mass input is 5,055 g/d, but after adjustment, the chorine mass input reduces to 3,336 g/d, a 34% reduction. More details of chlorine mass balance can be performed to understand the chlorine mass distribution in the system [17]. Accordingly, the MWA can reduce chlorine dosing rates to save the budget while maintaining the chlorine reliability of the system and avoiding users complaining of chlorine taste and odor.

We also calculated the original resilience index using the system chlorine mass input instead of the target one. While the original chlorine resilience index before chlorine management was 0.652, it was 0.622 after chlorine adjustment using the temporal TCRIs. As we reduce the chlorine concentration, the chlorine resilience will become worse.

However, a change of the chlorine resilience index after chlorine management means that the system chlorine resilience was not much after the chlorine mass reduction because chlorine decay mass depends not only on the decay constants but also on the chlorine mass in the system. Since we reduced the system mass input, there was less chlorine mass in the WDN to be decayed. Nevertheless, the new temporal TCRI values were close to 1.0, which means the target free residual chlorine concentration was met.

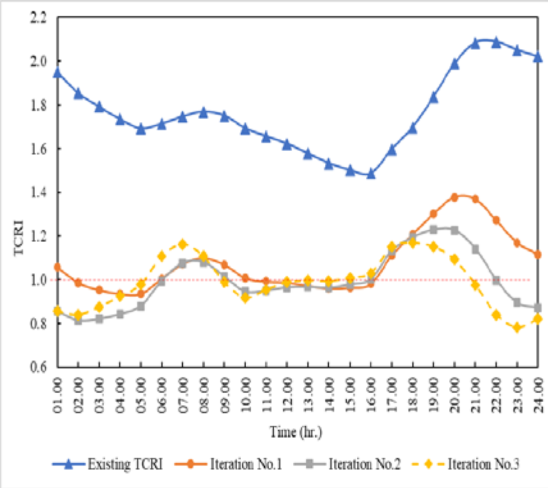

Fig. 10 Chlorine management iteration process

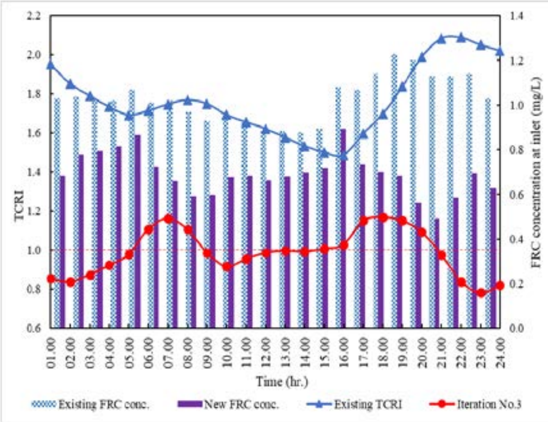

Fig. 11 TCRI adjustment for chlorine management

5. CONCLUSIONS

The resilience index by Todini can measure the reliability of WDNs when the pipe fails by calculating the surplus energy over available input energy. We modified the resilience index to include a target value of pressure and free residual chlorine concentration, so we could compare the delivery values to the target values. We applied both RIs to a district metering area on time and spatial aspects and investigated the impact of water loss on the RIs.

The THRI results of the whole network are 0.151 and 0.205 for WDNs with existing water loss (44.3%) and 19% of water loss, respectively. They imply that the average pressures of WDNs are 15.1% and 20.5% above the minimum pressure. By examining the temporal THRI, the time when the THRI approaches the target or below the service levels can be identified. In the spatial distribution of THRI, we can identify the low-reliability areas. Appropriate measures can be implemented accordingly. After reducing water loss, the THRIs are better in both time and space. Therefore, reducing water loss will make the WDNs more hydraulic reliable.

The results of TCRI of the whole network are 1.759 and 1.690 for WDNs with existing (44.3%) and 19% of water loss, respectively. They indicate that the WDN had 75.9% and 69.0% of FRC mass above the target FRC level. Both temporal and spatial TCRIs indicate where and when FRC problems occur for low and high chlorine contents. Therefore, the TCRI can help manage chlorine dosing rates in WDNs to improve reliability. After reducing water loss, the water age increases, so chlorine decays higher and the TCRI decreases. Unlike the THRI, water loss reduction hurts chlorine resilience.

We can use the temporal THRI and TCRI to estimate the pressure and chlorine inputs adjustments at the inlet for management purposes. We used the adjustment process and iterated until the THRI and TCRI values of the new pressure and chlorine inputs would approach 1.0. Because of the increment of pressure inputs, the overall THRI and resilience index by Todini increased to 0.999 and 0.439, respectively. On the opposite, the resilience index by Todini of new chlorine inputs decreased to 0.622 because of less chlorine mass inputs. The TCRI values after adjustment increased to 1.006. Therefore, higher pressure inputs can also improve THRI and original resilience index, but lower chlorine inputs affect low original resilience index but high TCRI. Hence, by using the THRI and TCRI we can assess the deficits of temporal and spatial resilience indices from targets which are useful for pressure and chlorine management to improve the WDNs' reliability.

6. ACKNOWLEDGMENTS

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