



## Evaluating the corrosiveness in drinking water distribution system in Yancheng City, China

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### ABSTRACT

In this paper, the chemical stability for tap water from water distribution system (WDS) and finished water from water treatment plants (WTP) of Yancheng City was evaluated by Langelier saturation index (LSI), Ryznar stability index (RSI), aggression index (AI), and Larson ratio (LR), respectively. The spatial and temporal variations of LSI, RSI, AI, and LR were analyzed and compared based on a total of 384 water samples including 256 tap water samples and 128 finished water samples collected monthly from September 2013 to December 2018. The objective of the paper is to reveal the spatial and temporal variation of chemical stability in tap water and finished water and the relationships between chemical stability and trihalomethanes (THMs), which was measured by gas chromatography equipped with an electron capture detector. Most samples have LSI values of lower than 0.0, RSI values of higher than 7.5, AI values of lower than 12.0, and LR values of higher than 0.5. The results indicated that both the tap waters from sampling sites of S1, S2, S3, and S4 and finished waters from WTP1 and WTP2 have the tendency of corrosion. In addition, the corrosion degree of tap water from S1 and S4 similar to treated water from WTP1 is less than the tap water from S2 and S3 similar to treated water from WTP2. Furthermore, the monthly variation of LSI and RSI values indicated that the chemical stability in summer with higher temperatures tends to scale, while the chemical stability in winter with lower temperatures tends to be corrosive. The monthly values of LSI, RSI, and AI have a close relationship with trichloromethane due to the effect of temperature. In the WDS of Yancheng City, the THMs primarily consist of bromodichloromethane, dibromochloromethane, and tribromomethane due to the effect of seawater intrusion that brings more brominated THMs. The results obtained can help managers understand and improve the chemical stability of tap water in WDS.

*Keywords:* Chemical stability; Corrosion index; Disinfection by-products; Water distribution system

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### 1. Introduction

In drinking water distribution systems (WDS), complicated physical, chemical, and biological processes lead to deterioration of chemical stability [1]. The chemical non-stabilized water leads to the occurrence of “red water”, that is, the water reached the consumers’ taps with yellow-brown red color. The “red water” phenomenon occurs worldwide in WDS, which decreases the service level of

local water authority [2,3]. The chemical non-stabilized water causes slow corrosion and the deterioration of metal pipes, which leads to leaking of water pipes. The corrosion products consume chlorine and create corrosion scales that increase the pump energy requirement, support the growth of biofilm, decrease the disinfection efficiency, and carry the sink of heavy metals or other contaminants [4,5]. The inorganic contaminants in WDS tend to accumulate in corrosion scale with concentration higher than

solution by several orders of magnitude. Under normal conditions, the release and deposit of iron oxides keep a relative equilibrium. However, under the condition of pipe scouring, the corrosion scale or biofilms were disturbed and iron oxides detached from the internal surface of metal pipes into the water, which leads to the occurrence of “red water” [6]. Since metal pipes are the most widely applied pipe material in the world, even unlined cast iron pipes still exist in some old and large cities, the “red water” events appeared all over the world. As such, chemical stable water is important for keeping the water supply safe and reliable. To provide safe drinking water, monitoring the chemical stability in WDS is an important concern of the water supply. However, the chemical stability in WDS is difficult and expensive to be monitored due to the corrosive and scaling tendency are affected by varieties of factors. As such, the chemical stability indices were developed [7]. Langelier saturation index (LSI) was proposed based on the difference between pH and pH of calcium carbonate saturation as a scale prediction parameter [8–11]. Ostfeld et al. [6] developed an optimization scheme with consideration of chemical stability measured by calcium carbonate precipitation potential (CCPP) in the water distribution system of mixing desalinated water and surface water and/or groundwater [12]. Aggression index (AI) was developed to select the asbestos cement pipes [13]. Imran proposed a modified form of the Larson ratio (LR) with consideration of the effects of temperature and hydraulic retention time based on apparent color release [14]. By now, there is no universal index for evaluating chemical stability, as such, the comparison among evaluation indices obtained from various aspects should be performed. In addition, in this paper, the relationship between the chemical stability evaluation index and trihalomethanes (THMs) was further analyzed, which can provide some information for assessing the chemical stability in tap water.

In this paper, firstly the corrosion index was introduced. Secondly, the corrosion index was applied to compare the chemical stability among two water treatment plants and four sampling sites along with the water distribution system of Yancheng City in China. Thirdly, the variation of chemical stability with time and space was analyzed, and the relationship between corrosion indices and disinfection by-products was analyzed. Finally, a conclusion was drawn.

## 2. Methodology

### 2.1. Chemical stability evaluation

#### 2.1.1. Langelier saturation index

The LSI had been applied to evaluate the chemical stability since the 1930s based on the theory that a calcium carbonate film on the pipe surface inhibits pipe corrosion and corrosion product release to some degree. It is an indicator to judge whether suitable conditions exist for the precipitation of calcium carbonate due to that calcium carbonate films inhibit corrosion, which was found by a preponderance of evidence [15]. Positive and negative LSI values indicate that the water is saturated and unsaturated with  $\text{CaCO}_3$ , respectively. Since unsaturated waters tend to remove the protective  $\text{CaCO}_{3(s)}$  scale and expose the

metal surface of the pipes to further corrosion, pH value is usually increased by 0.2–1 unit above  $\text{pH}_s$  (saturated pH value) to prevent corrosion in water distribution systems. However, LSI was recommended to be applied with caution since a study shows that a positive LSI was at least as corrosive as those with a negative LSI. The LSI value can be calculated by Eq. (1) as follows [14].

$$\text{LSI} = \text{pH} - \text{pH}_s = \text{pH} - (9.3 + N_s + N_t - N_h - N_a) \quad (1)$$

where  $\text{pH}_s$  is the saturated pH value,  $N_s$  is the dissolved solid constant,  $N_t$  is the temperature constant,  $N_h$  is the calcium hardness constant (mg/L  $\text{CaCO}_3$ ), and  $N_a$  is the total alkalinity constant (mg/L  $\text{CaCO}_3$ ). The values of  $N_s$ ,  $N_t$ ,  $N_h$ , and  $N_a$  can be obtained according to the total alkalinity, calcium hardness, total dissolved solids and water temperature [14]. The relationship between LSI and water chemical stability is shown in Table 1. The calculation of LSI has two disadvantages: (1) the water with the same LSI values may not be the same chemical stability due to the various pH values; (2) opposite conclusion may be obtained at LSI value of 0. To overcome the disadvantages of LSI values, the Ryznar stability index (RSI) was proposed by Ryznar.

#### 2.1.2. Ryznar stability index

In 1944 Ryznar proposed a stability index (RSI) based on the Langelier saturation index with only positive values produced. The RSI value of 6.5–7.0 indicated saturated water, while a value exceeding 7.0 indicates that no  $\text{CaCO}_{3(s)}$  was deposited. Although the RSI was based on the observations of  $\text{CaCO}_{3(s)}$  formed on glass tubing, it was found that the encrustation or corrosion of steel mains is a function of RSI. The RSI can be calculated by Eq. (2) as follows.

$$\text{RSI} = 2\text{pH}_s - \text{pH} \quad (2)$$

The chemical stability measured by RSI is close to the reality in some cases, however, it also has limitation due to the calculation is based on  $\text{pH}_s$ . As such, indicators of LSI and RSI can be applied together to judge the chemical stability. The relationship between RSI and water chemical stability is shown in Table 2 [15].

#### 2.1.3. Aggression index

The aggression index is applied to measure the tendency of water to deteriorate the structure of asbestos cement pipes, which is defined by Eq. (3) as follows.

$$\text{AI} = \text{pH} + \log(A \times H) \quad (3)$$

where  $A$  and  $H$  refer to total alkalinity and calcium hardness, respectively, mg/L  $\text{CaCO}_3$ . The AI values of 0–10, 10–12, and exceeding 12 are considered highly aggressive, moderately aggressive, and nonaggressive, respectively. The AI indicator is usually used as a stability index of water chemistry on the corrosiveness of asbestos cement pipes.

The three indices are proposed to measure chemical stability based on calcium carbonate precipitation. However,

Table 1  
Relationship between LSI and chemical stability

LSI	Chemical stability
>0	Dissolved carbonate in water is in supersaturated state and tends to produce calcium carbonate precipitation and scale
=0	Calcium carbonate dissolved in water is in equilibrium with the calcium carbonate in solid phase, and the water chemistry is stable
<0	Carbonate in water is unsaturated and the carbon dioxide is excessive, which tends to dissolve the solid calcium carbonate and has the tendency of corrosion

Table 2  
Relationship between RSI and chemical stability

RSI	Chemical stability
4.0~5.0	Serious scaling
5.0~6.0	Slight scaling
6.0~7.0	Basically stable
7.0~7.5	Slight corrosion
7.5~9.0	Serious corrosion
>9.0	Extremely serious corrosion

It was found that calcium carbonate film was sometimes rarely observed on pipe walls even under high positive LSI values. As such, the effectiveness of indices mentioned above for measuring iron corrosion needs to be verified due to the complexity of the involved reaction mechanisms. Besides calcium carbonate, a large number of water quality parameters as calcium, magnesium, conductivity, carbon dioxide, pH, chlorides, sulfates, conductivity, total dissolved solids, and silica should be considered [16].

#### 2.1.4. Larson ratio

The LR, put forward by Larson and Skold [17], was applied to evaluate water corrosivity in iron pipes with consideration of sulfate and chloride as corrosive factors and bicarbonate as an inhibitive factor [18]. Following research has found that elevated sulfate or chloride can increase corrosion product release in iron distribution pipes, while high bicarbonate concentration can significantly decrease iron corrosion product release. The LR can be expressed by Eq. (4) as follows.

$$LR = \frac{([Cl^-] + [SO_4^{2-}])}{[HCO_3^-]} \quad (4)$$

where  $[Cl^-]$ ,  $[SO_4^{2-}]$ ,  $[HCO_3^-]$  refer to the unit of  $Cl^-$ ,  $SO_4^{2-}$ , and  $HCO_3^-$  expressed in milliequivalents per liter. It is considered acceptable when LR values are less than 0.5. Higher LR values indicate higher corrosive water.

It was conducted that existing corrosion indices can only be applied to the specific case for which they were developed, and the single corrosion index cannot be applied universally. For example, the LR indicator is more suitable for old, corroded iron pipes. The focus of this study is to compare various chemical stability measures and reveal

the applicability of these indices for evaluating chemical stability in WDS.

#### 2.2. Study area

There are two water treatment plants (WTPs) termed WTP1 and WTP2 in Yancheng City, with the water sources of Tongyu River and Yanlong Lake ecological reservoir, respectively (shown in Fig. 1). The treatment process of WTP1 combined routine treatment processes of “grid reactor + horizontal sedimentation tank + V-type filter tank + clean water tank + pump station + chlorine disinfection” with advanced treatment technology of “pre-ozone + grid reactor + V-type filter + ozone bio-activated carbon tank + clean water tank + pump station + chlorine disinfection” with the treatment capacity of 300,000 m<sup>3</sup>/d. The treatment process of WTP2 is the routine treatment process of “tubular static mixer + vertical flow baffled reactor tank/grid reaction tank/grating reaction tank + inclined tube sedimentation tank + ordinary rapid filter/double valves filter/siphon filter + clean water tank + pump station + chlorine disinfection” with the treatment capacity of 115,000 m<sup>3</sup>/d. The raw water from the Mangshe River was purified using an ecological wetland to satisfy grade II water quality standards according to the surface water environmental quality standards in China (GB3838-2002) [19]. The tap water sampling locations in the water distribution systems are shown in Fig. 1, which were selected following the criteria of uniform distribution and stable hydraulic conditions [20,21]. The four sampling sites termed S1, S2, S3, and S4 were distributed in the most densely populated area in the main city and located at intersections with multiple flow paths, which are Eastern Garden, Central Blood Station, Yancheng Hotel, and Kangjian Hotel, respectively [22]. The pipe material at S1 and S4 is ductile iron pipe installed in 1990, and the pipe material at S2 and S3 is cast iron pipe installed in 2010 and 1985, respectively. A total of 384 water samples including 256 tap water samples and 128 finished water samples at the outlet of WTPs were collected monthly from September 2013 to December 2018. All samples were taken in the first week of each month, the same day of each week, following the same sampling route, and approximately at the same time to assure stability of hydraulic conditions. The system was flushed for about 3 min before collecting water samples to ensure the representativeness of the samples. Samples were collected in 50 mL screw vials with polytetrafluoroethylene caps, which were pre-cleaned by ultra-pure water and placed in an oven at 400°C for 1 h. The vials were rinsed with sampled water three times before sampling and were filled just to overflow without passing

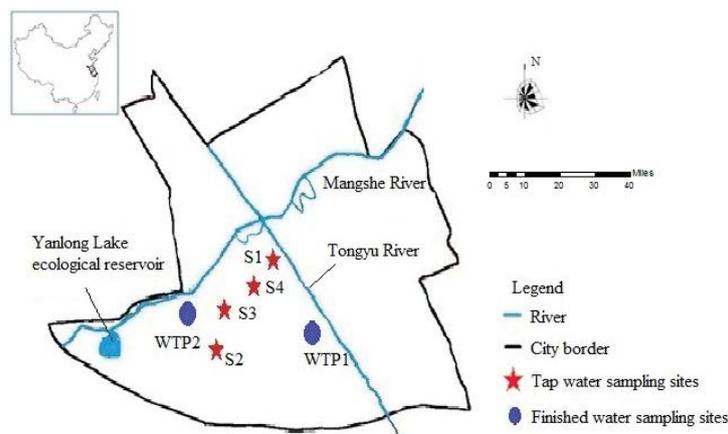


Fig. 1. Location of sampling sites in tap water and finished water.

air bubbles through the sample. To eliminate any remaining residual chlorine and to stop further trihalomethanes (THMs) formation, ascorbic acid (0.2 g) was added to vials. All samples were extracted within 24 h and analyzed within 5 d. Once collected, samples were stored in the dark at 4°C and carried to the laboratory for analytical procedures.

### 2.3. Analytical methods

Parameters of total dissolved solids (TDS), temperature, hardness, alkalinity, pH, chloride, and sulfate were measured by the standard analysis methods. To measure the THMs concentrations including trichloromethane (TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and tribromomethane (TBM), the water samples were prefinished following the USEPA 551.1 standard [23]. The liquid–liquid extraction was adopted by mixing a 20 mL water sample with a 4 mL methyl tert-butyl ether (MTBE), adding 8 g of sodium sulfate that has been dried for 2 h at 500°C to saturate the water sample and shaking for 3 min on the vortex oscillator. After standing for 30 min to facilitate phase separation, the upper organic layer 1.5 mL was transferred to the vial for analysis. The THMs were measured by gas chromatography (GC) equipped with an electron capture detector (ECD-Agilent 7890B, Shanghai, China). The THM calibration mix was purchased with a concentration of 1,000 µg/mL. The Agilent GC-7890B HP-5 capillary column (30.0 m × 250 µm × 0.25 µm nominal) was used for peak separation. The oven temperature regime for gas chromatography was as follows: initial temperature, 60°C for 2 min; first ramp of 10°C/min to 160°C (2 min); second ramp of 10°C/min to 200°C (2 min). The injector and detector temperatures were 230°C and 250°C, respectively.

## 3. Results and discussion

### 3.1. Description statistics

The TDS, water temperature, hardness, alkalinity, pH, chloride, and sulfate in finished water from WTP1 and WTP2 and tap water from S1, S2, S3, and S4 are listed in Table 3. The mean values of TDS of S1, S2, S3, S4, WTP1, and WTP2 are 221.0, 191.0, 196.0, 245.0, 223.0, and 207.0 mg/L,

respectively, which decreased in the order of S4 > WTP1 > S1 > WTP2 > S3 > S2. The mean temperature of S1, S2, S3, S4, WTP1, and WTP2 are 3.0°C, 4.6°C, 5.8°C, 3.2°C, 3.4°C, and 3.8°C, respectively, which decreased in the order of S3 > S2 > WTP2 > WTP1 > S4 > S1. From the related research, water from S2 and S3 was primarily supplied by WTP2, while the water from S1 and S4 was primarily supplied by WTP1 [22]. The values of TDS and temperature at S1 and S4 are closer to that at WTP1, while the values of TDS and temperature at S2 and S3 are closer to that at WTP2. The hardness of S1, S2, S3, S4, WTP1, and WTP2 ranged from 157.1 mg/L CaCO<sub>3</sub> to 222.0 mg/L CaCO<sub>3</sub>, which has no obvious regulation. The mean alkalinity of S1, S2, S3, S4, WTP1, and WTP2 are 132.0 mg/L CaCO<sub>3</sub>, 91.0 mg/L CaCO<sub>3</sub>, 91.3 mg/L CaCO<sub>3</sub>, 131.2 mg/L CaCO<sub>3</sub>, 132.0 mg/L CaCO<sub>3</sub>, and 91.2 mg/L CaCO<sub>3</sub>, respectively. The alkalinity of S1 and S4 are similar to that of WTP1, and the alkalinity of S2 and S3 are similar to that of WTP2. The chloride values of S1, S2, S3, S4, WTP1, and WTP2 are 37.0, 27.0, 34.0, 41.0, 43.0, and 26.0 mg/L, respectively, which decreased in the order of WTP1 > S4 > S1 > S3 > S2 > WTP2, which reflects the regulation of S1 and S4 are related to WTP1, and S2 and S3 are related to WTP2. The mean values of sulfate at S1, S2, S3, S4, WTP1, and WTP2 are 24.0, 25.0, 25.0, 24.0, 25.0, and 23.0 mg/L, respectively. Similar to hardness, the sulfate also had no obvious regulation. The TCM values of S1, S2, S3, S4, WTP1, and WTP2 are 4.0, 9.5, 10.0, 4.4, 1.1, and 5.2 µg/L, respectively. The TCM of S1 and S4 were affected by WTP1 primarily, and the TCM of S2 and S3 were affected by WTP2 primarily. The same regulation can also be obtained from BDCM and TBM. The BDCM values of S1, S2, S3, S4, WTP1, and WTP2 are 11.2, 24.1, 17.5, 10.6, 12.5, and 21.1 µg/L, respectively. Similarly, the TBM values of S1, S2, S3, S4, WTP1, and WTP2 are 16.1, 3.7, 7.1, 14.8, 14.9, and 5.1 µg/L, respectively. However, the regulation is not suitable for DBCM with the values of 21.9, 22.3, 20.0, 19.8, 23.2, and 21.5 µg/L for S1, S2, S3, S4, WTP1, and WTP2, respectively.

### 3.2. Chemical stability

The indices of LSI, RSI, AI, and LR were obtained by Eqs. (1)–(4). The comparison of four indices among sampling sites of S1, S2, S3, S4, WTP1, and WTP2 is shown in

Table 3  
Characteristics of water quality parameters in drinking water of Yancheng City

Site	Statistics	TDS (mg/L)	T (°C)	Hardness (mg/L CaCO <sub>3</sub> )	Alkalinity (mg/L CaCO <sub>3</sub> )	pH	Chloride (mg/L)	Sulfate (mg/L)	TCM (µg/L)	BDCM (µg/L)	DBC (µg/L)	TBM (µg/L)
S1	Min.	337.4	17.9	164.8	169.5	7.4	85.3	40.7	0.0	0.0	0.0	0.0
	Max.	473.0	32.2	222.0	224.0	7.8	139.0	70.0	22.0	41.0	56.0	46.0
	Mean	221.0	3.0	105.0	132.0	6.9	37.0	24.0	4.0	11.2	21.9	16.1
	SD	48.8	7.6	27.5	20.6	0.2	24.7	10.9	5.9	11.0	11.1	8.4
S2	Min.	332.9	18.2	157.8	156.7	7.5	73.6	39.9	0.0	0.0	0.0	0.0
	Max.	442.0	31.4	207.0	196.0	7.9	108.0	66.0	31.0	68.0	106.0	32.0
	Mean	191.0	4.6	107.0	91.0	7.3	27.0	25.0	9.5	24.1	22.3	3.7
	SD	46.7	7.9	25.5	20.8	0.1	18.4	10.2	8.5	11.2	16.7	7.3
S3	Min.	335.3	18.3	159.7	156.1	7.5	74.0	40.0	0.0	0.0	0.0	0.0
	Max.	436.0	30.8	206.0	196.2	7.8	121.0	67.0	35.0	60.0	94.0	32.0
	Mean	196.0	5.8	107.0	91.3	7.1	34.0	25.0	10.0	17.5	20.0	7.1
	SD	50.2	7.5	24.4	20.3	0.1	17.4	10.1	9.6	12.6	15.6	9.6
S4	Min.	343.4	18.1	164.3	170.8	7.5	84.9	40.9	0.0	0.0	0.0	0.0
	Max.	450.0	33.6	222.0	221.0	7.7	140.0	70.0	23.0	41.0	56.0	46.0
	Mean	245.0	3.2	109.0	131.2	7.1	41.0	24.0	4.4	10.6	19.8	14.8
	SD	44.9	8.3	26.8	20.4	0.1	23.7	10.7	6.7	11.1	13.1	9.4
WTP1	Min.	342.6	18.3	163.1	170.8	7.4	85.5	40.3	0.0	0.0	0.0	0.0
	Max.	475.0	32.6	215.0	224.0	7.7	152.0	66.0	10.0	35.0	55.0	35.0
	Mean	223.0	3.4	107.0	132.0	7.0	43.0	25.0	1.1	12.5	23.2	14.9
	SD	49.0	8.2	25.3	20.4	0.2	24.8	10.5	2.1	11.3	11.6	8.5
WTP2	Min.	334.0	18.2	157.1	156.1	7.5	71.2	38.9	0.0	0.0	0.0	0.0
	Max.	462.0	33.2	205.0	196.0	8.1	104.0	64.0	23.0	68.0	102.0	34.0
	Mean	207.0	3.8	101.0	91.2	7.3	26.0	23.0	5.2	21.1	21.5	5.1
	SD	48.8	8.3	24.9	20.5	0.1	17.3	9.8	6.0	13.2	16.7	8.2

Note: TDS refers to total dissolved solids; T refers to temperature; TCM refers to chloroform; BDCM refers to bromodichloromethane; DBCM refers to dibromochloromethane; TBM refers to tribromomethane.

Fig. 2. The mean values of LSI from four sampling sites of S1, S2, S3, S4 in WDS and two finished water from WTP1 and WTP2 are all lower than 0.0, which indicated that the tap water and finished water all have the tendency of corrosion. In addition, the mean LSI values for WTP1 are less than WTP2, which indicated that finished water from WTP1 is more corrosive than finished water from WTP2. The LSI values of tap water from four sampling sites of S1, S2, S3, and S4 decreased in the order of S3 > S2 > S4 > S1. The LSI values of tap water from sampling sites of S1 and S4 are less than those from S2 and S3. As mentioned before, S2 and S3 were primarily supplied by WTP2, while the water from S1 and S4 was primarily supplied by WTP1. Since the chemical stability of finished water from WTP1 is more corrosive than that from WTP2, the tap water from S1 and S4 is more corrosive than tap water from S2 and S3. As for RSI, the same regulation can be obtained. The mean values of RSI from S1, S2, S3, S4, WTP1, and WTP2 are all higher than 7.5, which indicated that the waters are all serious corrosive. The mean values of AI from S1, S2, S3, S4, WTP1, and WTP2 are all less than 12.0, which indicated that the waters are all moderately aggressive. The mean values of LR from S1, S2, S3, S4, WTP1, and WTP2 are all higher than 0.5, which indicated that the waters are all unacceptable from the view of chemical stability.

The annual variation of corrosion indices LSI, RSI, AI, and LR for S1, S2, S3, S4, WTP1, and WTP2 is shown in Fig. 3. For WTP1 and WTP2 the lowest LSI values occurred in 2016, while for S1, S2, S3, and S4, the lowest LSI values occurred in 2015, which are all lower than 0.0. The highest LSI value occurred in 2013 for almost all the sampling sites except for WTP2, which are all higher than 0.0. The results indicated that the chemical stability in 2016 and 2013 are corrosive and scaling, respectively. In most years, the LSI values are lower than 0.0, which indicated that the chemical stability in tap water and finished water has the tendency of corrosion. The same regulation can also be obtained from AI. The lowest AI values occurred in 2016 for all the sampling sites, which are lower than 12.0. The highest AI values occurred in 2013 for almost all the sampling sites except for WTP2. Similarly, in most of the years, the AI values are lower than 12.0, which also indicated that the chemical stability in tap water and finished water is moderately aggressive. Conversely, the highest RSI value occurred in 2016 except for S1 and S3, which are higher than 7.5. The lowest RSI value occurred in 2013 for all the sampling sites. In addition, in most of the years, the RSI values are higher than 7.5, which indicated that the chemical stability in most tap water and finished water is serious corrosion. As for LR, the highest LR value occurred in 2014,

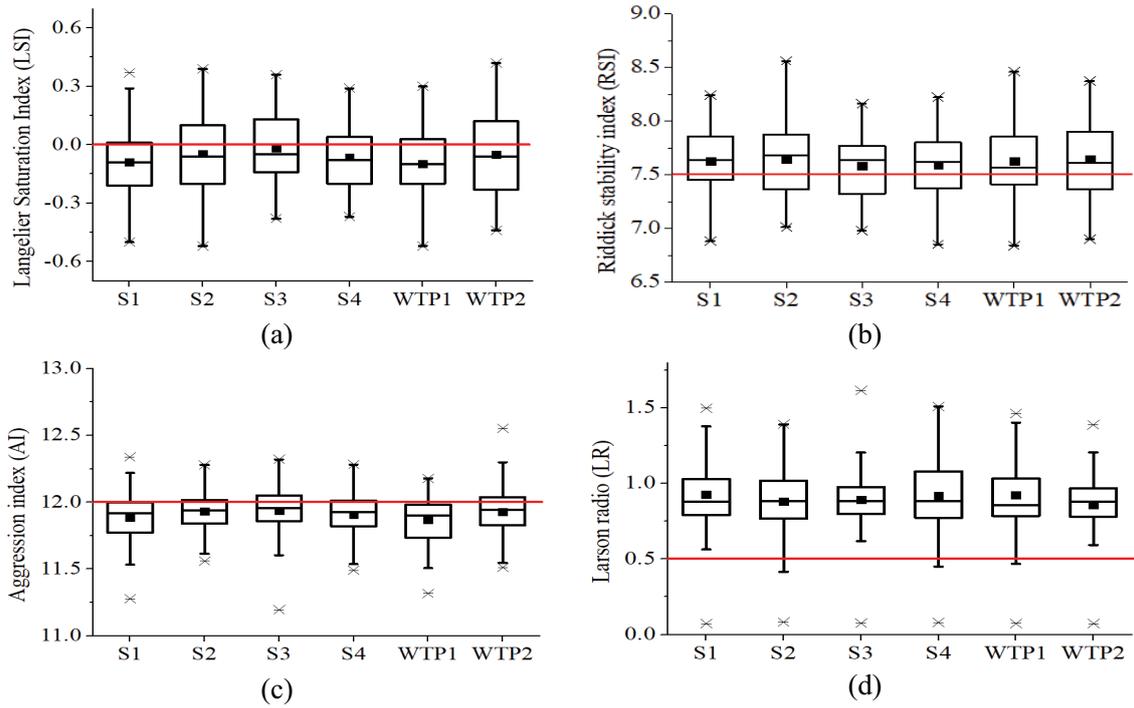


Fig. 2. Box plot of corrosion indices LSI (a), RSI (b), AI (c), and LR (d) for S1, S2, S3, S4, WTP1, and WTP2, respectively.

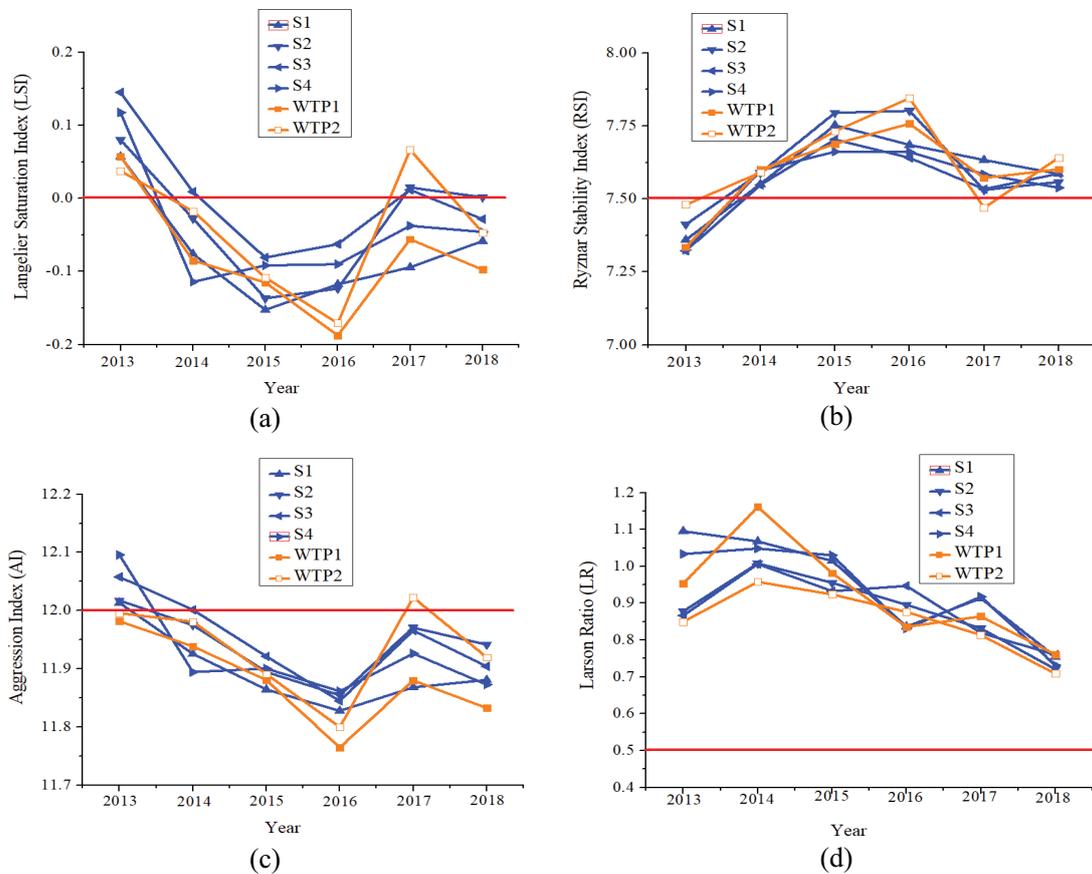


Fig. 3. Annual variation of corrosion indices LSI (a), RSI (b), AI (c), and LR (d) for S1, S2, S3, S4, WTP1, and WTP2, respectively.

while the lowest LR value occurred in 2018, which are all higher than 0.5. The results indicated that the tap water and finished water are all corrosive with a decreasing tendency.

The monthly variation of LSI, RSI, AI, and LR for S1, S2, S3, S4, WTP1, and WTP2 is shown in Fig. 4. The LSI values ranged from -0.3 to 0.1 with the tendency of inverted “V-shape”. The highest LSI value occurred in August, while the lowest LSI value occurred in February. In summer the LSI values with higher temperatures are higher than those in winter with lower temperatures. In most of the months, the LSI values are lower than 0.0, which indicated that the chemical stability of tap water and finished water has the tendency of being corrosive most of the time in one year. The RSI values ranged from 7.1 to 8.1 with the tendency of “V-shape”. Contrary to LSI, the highest RSI value occurred in February, while the lowest RSI value occurred in August. Moreover, the RSI values in summer with higher temperatures are lower than those in winter with lower temperatures. In most months, the RSI values are higher than 7.5, which indicated that the chemical stability of tap water and finished water is seriously corrosive. Since the temperature is the lowest in February and the highest in August, the corrosive degree has some relationship with temperature. When the temperature is higher in summer, the chemical stability tends to scale, while when the temperature is lower in winter, the chemical stability tends to be corrosive. The AI values ranged from 11.6 to 12.2 with the highest AI value occurring in March and December and

the lowest AI value occurring in June and July. In January, March, April, and December, the AI values are higher than 12.0, which indicated that the chemistry stability is non-aggressive, while in most of the months the AI values are between 10.0 and 12.0, which indicated that the chemical stability of tap water and finished water are moderately aggressive in most of the time. The AI values in months with higher temperatures are lower than those in months with lower temperatures. The results indicated that temperature has a negative relationship with an aggressive degree. The LR values ranged from 0.78 to 0.85, which are all higher than 0.5. The monthly variation of LR values has no obvious trend. In March, the LR values are much lower than those in the other months. The results indicated that LR values have no significant variation with months. Similar to the chemical stability obtained based on LSI, RSI, and AI, the higher LR values indicate that the chemical stability has the tendency of corrosion. Compared with the research on a city in Eastern China, the monthly variation of LSI, RSI, and AI are similar. In summer, the chemistry stability in WDS tends to scale, while in winter has the tendency of corrosion [24].

The relationships between THMs and chemical stability indices of LSI, RSI, AI, and LR including sampling sites of S1, S2, S3, S4, WTP1, and WTP2 from September 2013 to December 2018 are shown in Fig. 5a–d, respectively. The Pearson correlation coefficients among the parameters are summarized in Table 4. The results indicated that THMs have almost no relationship with LSI, RSI, AI, and LR with

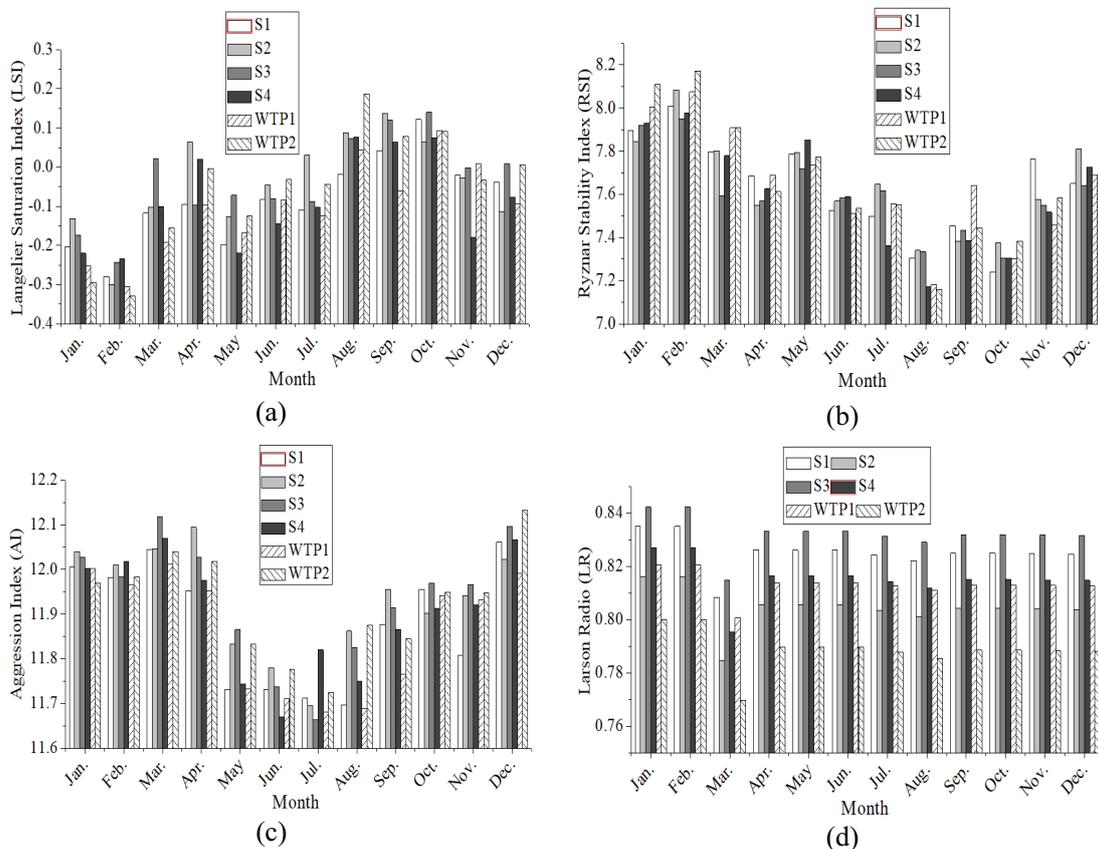


Fig. 4. Monthly variation of corrosion indices LSI (a), RSI (b), AI (c), and LR (d) for S1, S2, S3, S4, WTP1, and WTP2, respectively.

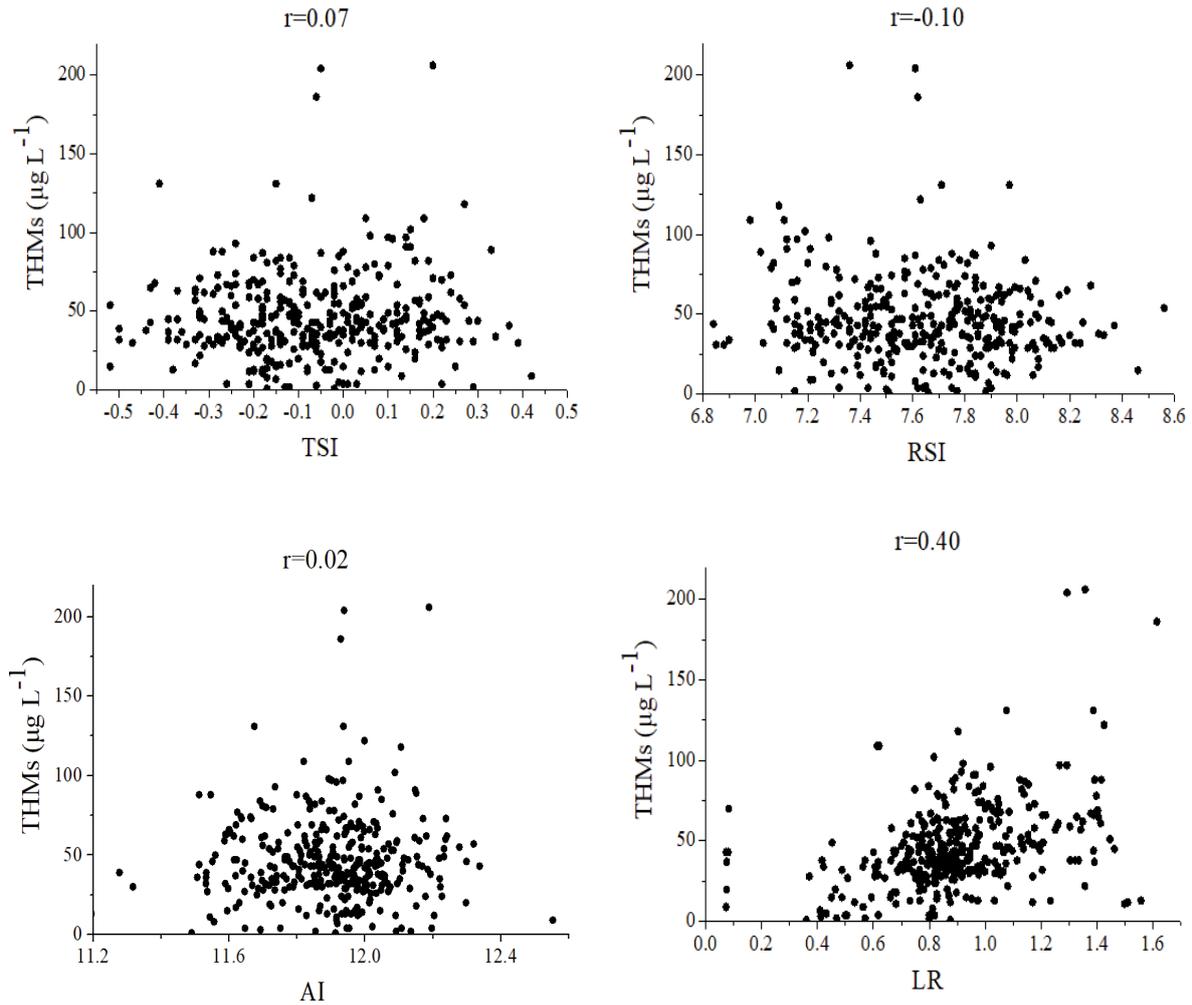


Fig. 5. Relationships between chemical stability index (a) LSI, (b) RSI, (c) AI, (d) LR and THMs.

Table 5  
Correlation matrix between monthly chemical stability index and THMs, TCM, BDCM, DBCM, and TBM

Parameters	LSI	RSI	AI	LR	THMs	TCM	BDCM	DBCM	TBM
LSI	1.00								
RSI	-0.95	1.00							
AI	-0.24	0.49	1.00						
LR	-0.49	0.42	0.06	1.00					
THMs	0.34	-0.39	-0.21	-0.25	1.00				
TCM	0.72	-0.83	-0.61	-0.16	-0.01	1.00			
BDCM	0.43	-0.40	0.01	-0.17	0.90	0.03	1.00		
DBCM	0.20	-0.22	-0.08	-0.17	0.97	-0.21	0.87	1.00	
TBM	-0.06	0.02	-0.08	-0.22	0.87	-0.40	0.65	0.92	1.00

Pearson correlation coefficients of 0.07, -0.10, 0.02, and 0.4, respectively.

To discover the temporal variation of chemical stability indices and THMs species, the parameters for sampling sites of S1, S2, S3, S4, WTP1, and WTP2 were averaged according to a month to obtain monthly data. The Pearson

correlation coefficients between monthly chemical stability indices and THMs, TCM, BDCM, DBCM, and TBM are shown in Table 5. Similar to the relationship mentioned above, the relationships between monthly chemical stability indices of LSI, RSI, AI, and LR and THMs are uncorrelated with coefficients of 0.34, -0.39, -0.21,

and  $-0.25$ , respectively. However, the monthly chemical stability indices of LSI, RSI, and AI have relationships with TCM with correlation coefficients of  $0.72$ ,  $-0.83$ , and  $-0.61$ , respectively, while having no relationship with BDCM, DBCM, and TBM with absolute values of correlation coefficients less than  $0.50$ . The monthly chemical stability index of LR has no relationship with TCM, BDCM, DBCM, and TBM (also shown in Fig. 6). The results indicated that chemical stability in WDS was closely related to TCM. The reason is that the concentration of TCM is affected by temperature in WDS, which also affects the chemical stability indices of LSI, RSI, and AI mentioned above. However, the THMs concentration primarily consists of BDCM, DBCM, and TBM with correlation coefficients of  $0.90$ ,  $0.97$ , and  $0.87$ , respectively. Since Yancheng City is located in a coastal area with large areas of saline-alkali beaches, the brominated THMs increased due to seawater intrusion and upstream industrial pollution.

#### 4. Conclusion

In this paper, the corrosion indices of LSI, RSI, AI, and LR were introduced and applied for evaluating the chemical stability of the four sampling sites of S1, S2, S3, and S4 and the two water treatment plants of WTP1 and WTP2 in Yancheng City in China. The spatial and temporal

variations of LSI, RSI, AI, and LR were analyzed and compared. The results indicated that waters from both tap water and finished water have the tendency to corrosion. In addition, the chemical stability of finished water from WTP1 is more corrosive than finished water from WTP2, which leads to the tap water from S1 and S4 primarily supplied by WTP1 being more corrosive than tap water from S2 and S3 primarily supplied by WTP2. According to LSI, RSI, and AI, the chemical stabilities are scaling in 2013 and corrosive in 2016, while according to the LR index the corrosion tendency has been reduced in recent years. The highest corrosion degree occurred in February, while the lowest corrosion degree occurred in August, which has a negative relationship with temperature. The conclusion is in accordance with the previous study, that is, the tendency of water toward scaling has been accelerated by increasing the water temperature [24]. The reason is that temperature affects dissolved oxygen and the dispersion velocity of ions, which influences the corrosion tendency of WDS. In general, the chemical stability indices almost have no relationship with THMs. However, the monthly chemical stability indices of LSI, RSI, and AI have a close relationship with disinfection by-products TCM, while having no relationship with BDCM, DBCM, and TBM. The TCM is primarily formed through the reaction between chlorine and natural organic matter in WDS, which is affected by

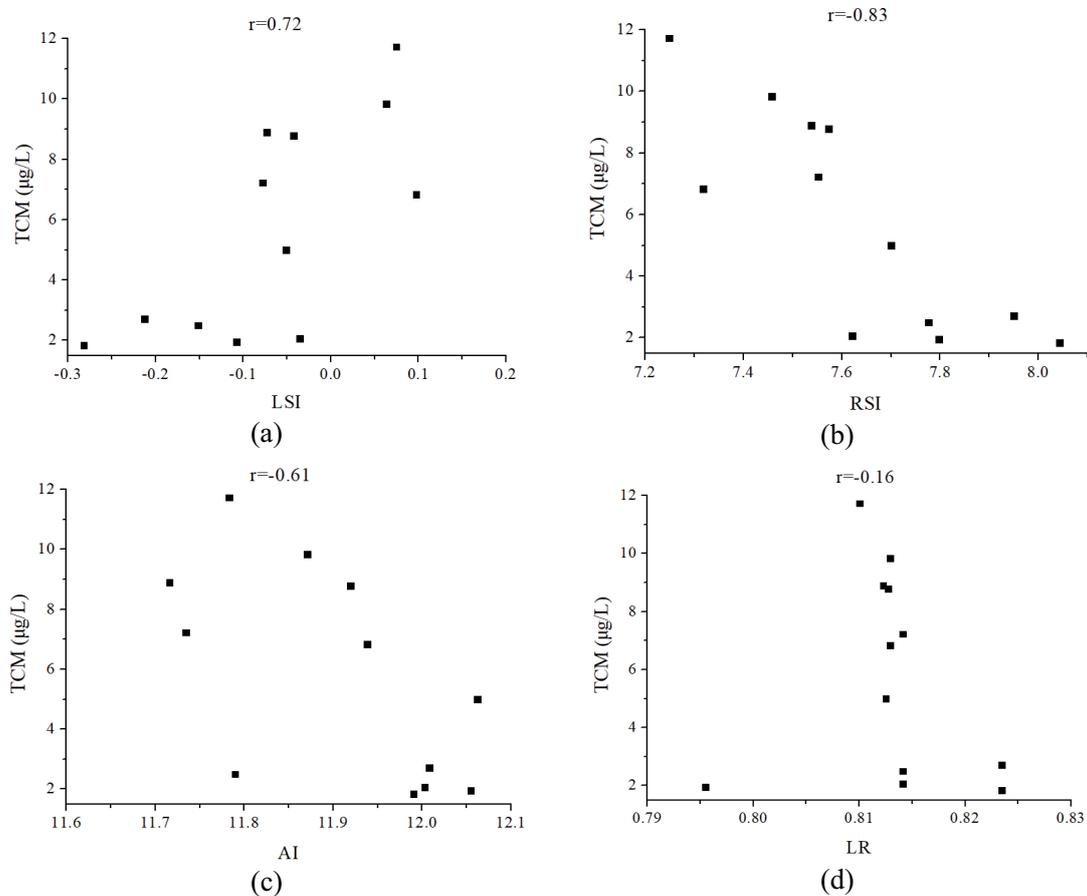


Fig. 6. Relationships between monthly chemical stability index (a) LSI, (b) RSI, (c) AI, (d) LR and TCM.

Table 4  
Correlation matrix between chemical stability index and THMs

Parameters	LSI	RSI	AI	LR	THMs
LSI	1.00				
RSI	−0.92	1.00			
AI	0.44	−0.12	1.00		
LR	−0.28	0.28	0.02	1.00	
THMs	0.07	−0.10	0.02	0.40	1.00

temperature. The chemical stability indices of LSI, RSI, and AI can also reflect the effects of temperature. As such, the relationship between monthly chemical stability indices of LSI, RSI, and AI and TCM is significant. The monthly chemical stability index of LR has no relationship with TCM, BDCM, DBCM, and TBM due to LR index does not reflect the effect of temperature. In WDS of Yancheng City, more bromide was brought to form brominated THMs which are affected by seawater intrusion, the concentration of THMs primarily consists of BDCM, DBCM, and TBM. Since the corrosion mechanism is complex, calcium carbonate film may rarely be observed on pipe walls even with high positive LSI values. In future research, to avoid the possible risks of assessing the chemical stability based on limited indices, more chemical stability indices should be considered and a modified LR index should be proposed. The results obtained can give more information for assessing chemical stability and analyzing the relationship between the tap water from WDS and finished water from WTPs.

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