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Effects of rainfall characteristics on corrosion indices in Korean river basins

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ABSTRACT

Corrosion indices have been widely used to assess water quality in countries such as the USA, Japan, France, and The Netherlands since Langelier first introduced this concept in 1936. The most commonly used corrosion indices are the Langelier saturation index (LSI), the Ryznar stability index (RSI), and the aggressiveness index (AI). Here, the changes in LSI, RSI, and AI due to corrosion factors such as pH, Ca hardness, and alkalinity were characterized according to the rainfall during the rainy season at four river basins in Korea. The results of a sensitivity analysis of corrosion indices with varying corrosion factors showed that pH had the greatest effect with a value of 0.1, which indicates that pH affects corrosion more than any other corrosion factor. By comparing the monthly pattern of corrosion factors at each river, it was found that pH and alkalinity decreased during the rainy season, whereas Ca hardness showed only subtle changes across the year. In addition, when comparing the relationship between the corrosion factors and corrosion indices at each river basin in the rainy season, LSI, RSI, and AI all showed strong corrosiveness with values of −2.97, 12.80, and 9.26, respectively, in the Nakdong River basin.

Keywords: Corrosion index; Rainfall characteristics; Langelier saturation index; Ryznar stability index; Aggressiveness index

1. Introduction

Korea has recently introduced highly improved water treatment technology and expanded the use of advanced water treatment processing in the main cities to improve the aesthetics of treated water by removing unpleasant tastes and odors. In spite of these efforts to provide healthy and pleasant water, Korean citizens continue to mistrust the quality of tap water. According to the Ministry of Environment, 11.7% of reasons why people cannot trust tap water relate to household drinking water having shown visible evidence of corrosion in the form of rust. Treated

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water provided from water treatment plants (WTPs) has been hard to maintain its high quality through the supply process after the initial production stage [1]. There are various ways of maintaining the quality of tap water throughout the supply process; these are largely divided between the removal and regeneration of old pipes, periodic washing, and reducing the corrosiveness of tap water.

Corrosion indices have been widely used to assess the corrosiveness of tap water since Langelier first introduced the corrosion index in his paper in 1936 [2]. The most commonly used corrosion indices are the Langelier saturation index (LSI), the Ryznar stability index (RSI), and the aggressiveness index (AI). Corrosion indices are used to grade the extent to which tap water affects the corrosion of water supply pipes. Usually, this grade is evaluated by the index based on the precipitations of $CaCO_3$ and resulting values of LSI, RSI, and AI that are calculated [3–5]. Corrosion inside the water supply pipes is generated by contact between the pipe surface and the surrounding environment, including exposure to water. This corrosion is affected by physical factors such as flow rate and temperature, the type and quality of the pipe material, and chemical factors such as pH, alkalinity, Ca hardness, temperature, and the concentration of total dissolved solids (TDS), chloride, sulfate, dissolved oxygen, and silica [6].

However, it is not easy to conceptualize these factors and to define them mathematically. As a result, LSI is only used routinely in advanced countries such as the USA, Japan, France, and The Netherlands. The standard of water quality in Japan indicates that the LSI should be maintained in the range of −1.0–0, as the lowest acceptable value of pH is 5.8 [7]. In USA, the National Secondary Drinking Water Contaminant Regulations define the standard of corrosiveness, and define water as being noncorrosive when the pH is 6.5 [8].

Recently, Ministry of Environment in Korea has chosen to monitor drinking water using the LSI, and since 2011, the water quality in each WTP has been monitored. This effort aims to reduce the rust in tap water due to the corrosion in the pipes, and to lower the rate of deterioration of water supply and drainpipes [8,9]. The rainfall in Korea has increased about 20% over the last 10 years and this consistently increasing pattern of rainfall has been shown to result from global warming. The average annual rainfall of Korea is 1,200 mm, about double the world average. However, the increases in rainfall occur during the rainy season (June–September). This reduces the pH and alkalinity encountered during the water treatment process, which also reduces the LSI and is associated with high levels of corrosiveness [10].

Therefore, it is necessary to analyze the corrosiveness in WTPs associated with the increased rainfall during the rainy season. In this research, the rainfall characteristics in four river basins were studied. The sensitivity of corrosion indices (LSI, RSI, and AI) to the different corrosion factors seen in each river basin was evaluated. The effects that corrosion factors have on values of LSI were also studied, and a comparison was made of the corrosion indices at each river basin.

2. Materials and methods

2.1. Outline of each river basin

WTPs managed by the Korean Water Resources Corporation (K-water) were categorized into four river basins with three WTPs in each river basin. The rainfall distribution and capacity of WTPs were therefore investigated in 12 WTPs.

Table 1 shows the capacity of three WTPs per river basin. The capacities of WTPs at the Han and Geum River basins show that they are five times larger than WTPs in the Nakdong and Yeongsan River basins. Fig. 1 shows the location of the river basins studied in this research. In this study, the focus was the analysis of data relating to purified water rather than original water during the 12 months of 2009.

To determine the annual rainfall in 2009, average rainfall data were obtained by using the Data Extractor program provided by the Korea Meteorological Administration. This information documented the rainfall in the relevant cities for a total of 12 WTPs in the four river basins.

2.2. Corrosion index according to corrosion factors in the river basin

The three corrosion indices evaluated in this study (LSI, RSI, and AI) can be defined as follows [11]. Each corrosion index is expressed in Eqs. (1)–(3).

$$\mathrm{LSI} = \mathrm{pHa} - \mathrm{pHs} \tag{1}$$

$$\mathrm{RSI} = 2\mathrm{pHs} - \mathrm{pHa} \tag{2}$$

$$\mathrm{AI} = \mathrm{pHa} + \log(C \times D) \tag{3}$$

pHa is the value of pH that has been actually measured in the study; pHs in Eq. (4) indicates the value of water quality factors when saturated by $CaCO_3$. When LSI is larger than 0, scale is generated in the pipe, and when LSI is smaller than −2.0, it shows a

Table 1
Capacity of WTPs per river basin

Basin	WTP name	Capacity (m^3/d)	Basin	WTP name	Capacity (m^3/d)
Han River	H1	258,000	Nakdong River	N1	70,000
	H2	711,000		N2	80,000
	H3	250,000		N3	10,000
Geum River	G1	414,000	Yeongsan River	Y1	100,000
	G2	596,000		Y2	30,000
	G3	421,000		Y3	200,000

Fig. 1. Geographic distribution of river basins in Korea.

strong corrosiveness. When RSI is smaller than 5.5, scale is generated, and when larger than 8.5, it shows high corrosiveness. Finally, when AI is close to 6.8, scale is generated, and strong corrosiveness occurs when close to 10.

$$\text{pHs} = \{(9.3 + A + B) - (C + D)\} \tag{4}$$

A–D in Eq. (4) are defined as follows: $A = (\log_{10}[\text{TDS, mg/L}] - 1)/10$; $B = -13.12 \times \log_{10}(T, ^\circ\text{C} + 273) + 34.55$; $C = \log_{10}[\text{Ca hardness, mg/L as } CaCO_3] - 0.4$; $D = \log_{10}[\text{alkalinity, mg/L as } CaCO_3]$. By selecting three corrosion factors that affect the corrosion indices, the relationship between corrosion factors and corrosion indices was compared and analyzed in each river basin during the rainy season.

2.3. Sensitivity of LSI, RSI, and AI to corrosion factors

To identify the sensitivity of corrosion indices to corrosion factors, one corrosion factor was set to a constant value and the effects of changing other corrosion factors were observed. This allowed comparison and analysis of how the corrosion factors affect the different corrosion indices. Table 2 summarizes the corrosion factors evaluated and the numeric values used in the sensitivity analysis. By setting the pH of each corrosion factor to a fixed value of 7.1, the water temperature to 14°C, TDS to 75 mg/L, Ca hardness to 32 mg/L, alkalinity to 25 mg/L, and the value of the other corrosion factors being changed as shown in Table 2, the sensitivity ratio can be calculated for each corrosion index (LSI, RSI, and AI).

2.4. Comparative analysis of LSI, RSI, and AI

To study further the characteristics of different corrosion indices, each corrosion index was evaluated by comparing and analyzing the values at each of the four river basins. The corrosion strength associated with each corrosion index was examined by comparing the

Table 2
Summary of corrosion factors used in the sensitivity analysis

Corrosion factors	pH	Temperature (°C)	TDS (mg/L)	Ca hardness (mg/L)	Alkalinity (mg/L)
pH	5–8	14	75	32	25
Temperature	7.1	3–24	75	32	25
TDS	7.1	14	45–110	32	25
Ca hardness	7.1	14	75	15–50	25
Alkalinity	7.1	14	75	32	10–40
Interval	0.1	1	1	1	1

values of LSI and RSI. In addition, corrosion indices were compared with AI, which was derived from LSI.

3. Results and discussion

3.1. Rainfall characteristics by river basin

The climate of Korea is monsoonal with rainfall being four times greater in summer than in winter as shown (Fig. 2). The corrosion indices evaluated in this study are believed to reflect a change in corrosion characteristics due to changes in corrosion factors found during the rainy season. Since 1910, the average annual rainfall has increased by approximately 19%, representing an increase of 200 mm during the twentieth century [12]. In particular, the annual rainfall of Seoul (Han River basin) has increased to an average annual amount of 1344.2 mm. This mainly occurs during the summer season, with rainfall during the period July–August representing 60.2% of the annual total rainfall [12]. Fig. 2 compares the rainfall characteristics of each region, with the Han River basin receiving the largest rainfall during the rainy season.

Two-thirds of the annual rainfall occurred during the rainy season (June–September, months 6–9; Fig. 2), and the Nakdong River basin shows the highest July rainfall of any region. The total rainfall in each region during the rainy season, in order from highest to lowest, was: Han River basin > Nakdong River basin > Yeongsan River basin > Geum River basin.

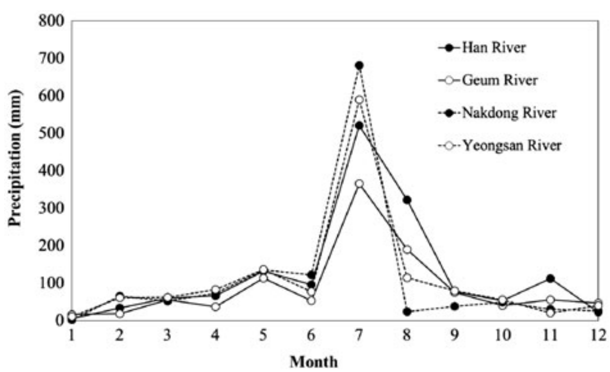

Fig. 2. Rainfall characteristics by each river basin (2009).

3.2. Sensitivity of corrosion factors on LSI, RSI, and AI

Various factors cause corrosion in water supply pipes and corrosion factors such as pH, water temperature, TDS, Ca hardness, and alkalinity help to define the corrosion tendency of the surrounding

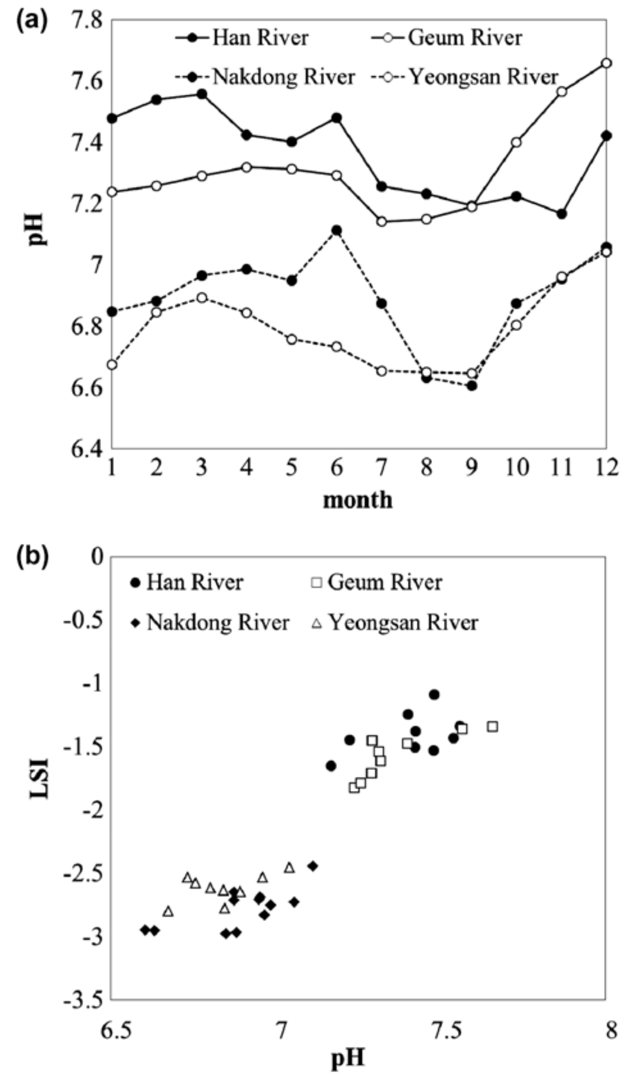

Fig. 3. (a) Monthly pH, and (b) LSI vs. pH at each river basin.

Table 3
Sensitivity of LSI, RSI, and AI to different corrosion factors

Corrosion index	pH	Temperature (℃)	TDS (mg/L)	Ca hardness (mg/L)	Alkalinity (mg/L)
LSI	0.1	0.02	−0.001	0.028	0.04
RSI	−0.1	−0.04	0.001	−0.05	−0.2
AI	0.1	–	–	−0.05	−0.08

environment. In this research, the influence of these corrosion factors on LSI, RSI, and AI was evaluated using sensitivity analysis. Of these five factors, pH has the greatest impact on the corrosion indices. As shown in Table 3, pH shows a sensitivity of 0.1 for LSI and AI, and −0.1 for RSI. These values of sensitivity, which are all higher than the other sensitivity values, indicate that pH affects the corrosion indices to a greater extent than the other corrosion factors.

Sensitivity of alkalinity is 0.04, Ca hardness is 0.028, and temperature is 0.02. Therefore, it is considered that the most effective method of preventing corrosion in pipes is by reducing the pH. The order of sensitivity of the corrosion indices to the corrosion factor is as followings: pH > alkalinity > Ca hardness > temperature > TDS.

Raw water quality changes during the rainy season require the use of coagulants and disinfectants during water treatment, which can affect pH levels [13]. Similarly, in cities with serious air pollution, NO_X and SO_X may be present in increased quantities due to increased run-off during the summer months, thereby lowering the pH during the rainy season. Another reason for the decrease in pH can be attributed to increase in organic matter brought about by rains which result in decrease in dissolved oxygen through the utilization of organic dehydration [14]. Such effects may significantly influence the corrosion indices, due to the high sensitivity of these indices to pH.

3.3. LSI analysis according to corrosion factors by river basin

In drinking water quality standard of Korea, the lowest acceptable value of pH is 5.8, which is lower than that of advanced countries. Most surface water that is used as drinking water in Korea has low alkalinity and pH. This might be the cause of the strong corrosiveness shown in tap water [2]. The pH values shown in the four river basins in Korea are higher than this lower limit (Fig. 3(a)). There is a decrease shown in pH during the rainy season, indicating that the pH levels are affected by the amount of rainfall. As pH decreases, LSI also decreases corresponding to a more corrosive environment (Fig. 3(b)). The LSI in all four river basins had values lower than −1.0, demonstrating a range from weak to strong corrosion tendencies.

Some parts of the water resource have positive LSI values, but negative LSI values are always seen in the purification process. Negative values of LSI in tap water are associated with a strong corrosiveness tendency, and this may also result from the injection of coagulants and liquefied chlorine gas for disinfection during the purification [13]. In general, the presence of chloride ions causes corrosion in pipes by preventing the activation of inactivated surfaces reacting to metal [15]. An alternative is to change from using liquefied chlorine gas, which causes a decline in the pH of treated water, to sodium hypochlorite, which increases the pH.

Since each river basin has its own water resource environment, all pH values appear to be different. According to the change in rainfall during the rainy season, the Han River basin has the highest pH and the Nakdong River basin has the lowest pH. Fig. 3(b) shows that LSI is −1.46 at a pH value of 7.19 in the Han River basin, and LSI is −2.94 at a pH value of 6.60 in the Nakdong River basin. This shows that Nakdong River basin has stronger corrosiveness than Han River basin: Nakdong River > Yeongsan River > Geum River > Han River. Overall, the values of the pH and LSI in the Han and the Geum River basins are similar, as are the values of the pH and LSI in the Nakdong and the Yeongsan River basins.

Table 4
Corrosion control required to achieve LSI values > –1.5

	Raw water pH < 7.0 Alkalinity (mg/L)			Raw water pH > 7.0 Alkalinity (mg/L)		
Range	<10	10–20	>20	<10	10–20	>20
LSI < –2.5	(Liquid) potassium hydroxide + carbon dioxide					
–2.5 < LSI < –2.0	(Liquid) potassium hydroxide + carbon dioxide	(Liquid) potassium hydroxide + carbon dioxide	Potassium hydroxide + sodium hydroxide	(Liquid) potassium hydroxide + carbon dioxide	Potassium hydroxide + sodium hydroxide + carbon dioxide	Potassium hydroxide + sodium hydroxide
–2.0 < LSI < –1.5	Potassium hydroxide + sodium hydroxide					

The control of corrosion in tap water is a process with injecting alkaline chemicals that increases the pH, alkalinity, and Ca hardness in the water (Table 4). Alkaline chemicals such as potassium hydroxide and sodium hydroxide are used. However, injecting excessive amounts of potassium hydroxide causes an increase in expenses associated with the regular management and maintenance of WTPs, as well as incidental expenses incurred by chemical storage requirements. Therefore, there are practical limits to the amount of chemicals that are used.

In all river basins, alkalinity followed a pattern of decreasing levels in the rainy season, showing a direct relationship with the rainfall amounts during this time (Fig. 4(a)). In the Geum River basin, the alkalinity during the rainy season decreased more rapidly than that in the other river basins. An alkalinity concentration of 10.58 mg/L in the Nakdong River basin was associated with an LSI of −2.94, indicating a strong tendency for corrosion. The alkalinity of 35.51 mg/L in the Han River basin correlated with an LSI of −1.46, representing medium corrosiveness (Fig. 4(b)). The corrosiveness of raw water in the Geum River basin is stronger than that in the Han River; however, the quality of treated water produced in the Geum River basin by corrosiveness control during the water purification process has been improved to a level similar to that of the Han River. This has occurred by raising the corrosion index of tap water through the injection of alkaline chemicals in the water purification process [13].

Calcium, which has been used as a major factor in calculating corrosion indices such as LSI, RSI, and AI, plays an important role in protecting the cement lining of water supply pipes. A lining of cement is applied to concrete, steel, and ductile cast iron pipes, and when these pipes have a high concentration of calcium it suppresses the elution of calcium from the lining and protects the lining material. When the water has an appropriate concentration of calcium, it improves the taste of the water, and it is has been suggested that corrosiveness control of tap water can contribute to the reduction of rust and improvement in the water aesthetics [16].

The change in Ca hardness concentration for each month in the four river basins is shown in Fig. 5(a). As previously mentioned, the pH and alkalinity showed changes according to the amount of rainfall, particularly during the rainy season. However, Ca hardness values do not show any notable changes due to increased rainfall. Since the Han and the Geum River basins have higher Ca hardness concentrations compared with the Nakdong and the Yeongsan River basins, we might expect to see a slight change in the corrosiveness. From Fig. 5(b), it can be seen that the Han and the Geum River basins have a similar range of LSI values. When the Ca hardness concentration of the Han River basin is 42.12 mg/L, the LSI is −1.46 and when the Ca hardness concentration of the Nakdong River basin is 23.14 mg/L, the LSI is −2.94, which shows strong corrosiveness. Many countries have recommended a preferred range in Ca hardness concentration in order to protect the water supply pipes, including Norway 15–25 mg/L, Finland 20–30 mg/L, and Sweden 20–60 mg/L. The annual range of Ca hardness concentration is 19.9–48.6 mg/L in these four river basins. A recommended range of Ca hardness concentration does not yet exist, but the recommendation for total hardness is below 300 mg/L [6]. In winter, when

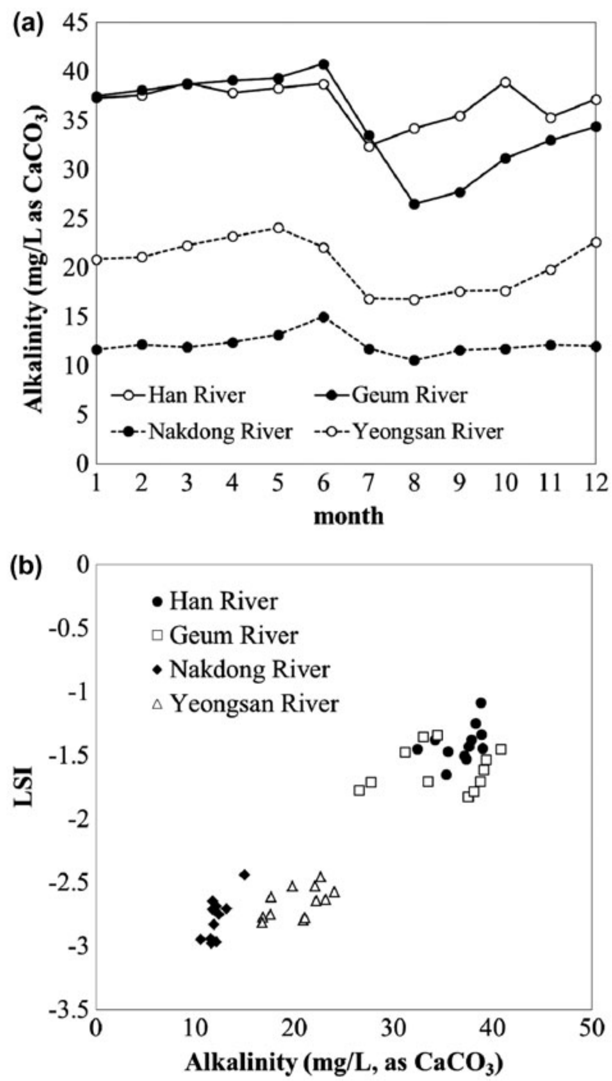

Fig. 4. (a) Monthly alkalinity levels (mg/L as $CaCO_3$), and (b) LSI vs. alkalinity (mg/L as $CaCO_3$), at each river basin.

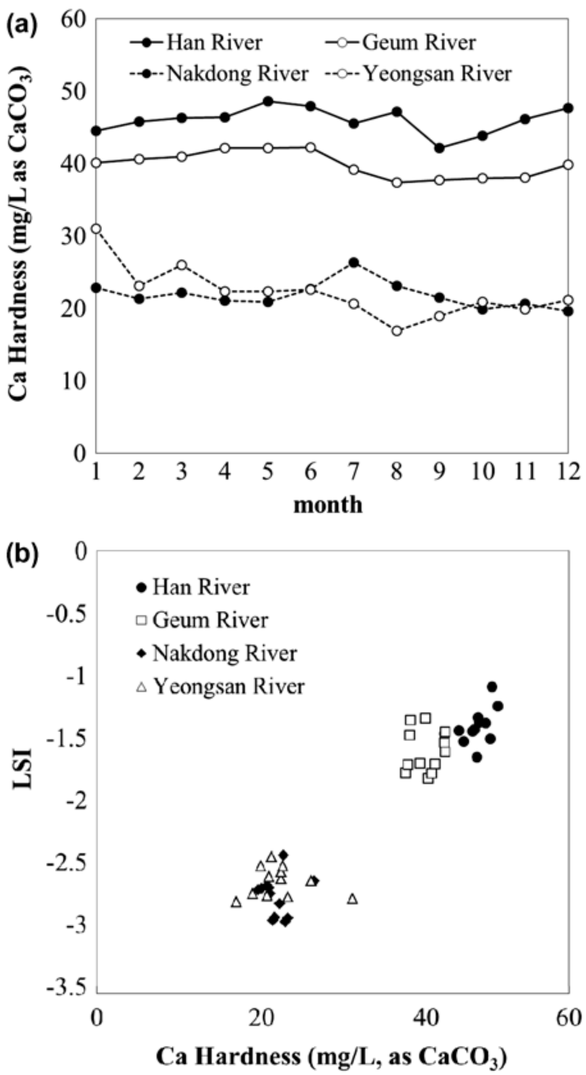

Fig. 5. (a) Monthly distribution of Ca hardness (mg/L as $CaCO_3$), and (b) LSI vs. Ca hardness (mg/L as $CaCO_3$) in each river basin.

the water temperature is low, the temperature drops to 0˚C and in summer the temperature jumps to as high as 25˚C. Therefore, higher concentrations of Ca hardness and alkalinity are required during winter [10].

3.4. Comparison and analysis of LSI, RSI, and AI at each river basin

The corrosion indices used in this research were LSI, RSI, and AI. All corrosion indices are calculated using the same corrosion factors. However, these indices are adapted to the individual characteristics of each corrosion factor. LSI is an index that can predict

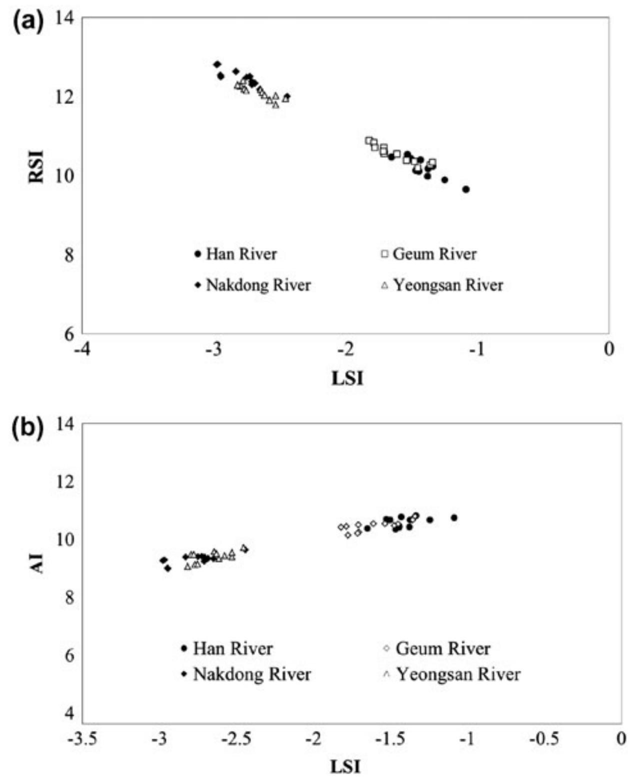

Fig. 6. (a) Comparison and analysis of LSI vs. RSI, and (b) comparison and analysis of LSI vs. AI.

the precipitation of $CaCO_3$ in the surface of the pipe, presenting as a thin layer. RSI is a function of the $CaCO_3$ index that provides information about the speed of corrosion and layer formation in the steel pipe.

AI is a simplified version of LSI that was developed to predict corrosiveness based on the $CaCO_3$ saturation state. Fig. 6(a) indicates the characteristics of corrosion in each river basin by comparing the values of LSI and RSI. The LSI values of the Han and the Geum River basins show medium corrosiveness whereas the RSI values in both rivers show strong corrosiveness. Both the LSI and RSI values in the Nakdong River basin show strong corrosiveness, –2.94 and 12.53, respectively. In general, the pH and the LSI values in the Han and the Geum River basins were similar, as the pH and LSI in the Nakdong and the Yeongsan River basins also being similar. Fig. 6(b) indicates the corrosion characteristics in each river basin by comparing values of LSI and AI. The LSI and AI values of the Han and the Geum River basins show medium corrosiveness, whereas the LSI and AI values of the Nakdong and the Yeongsan River basins show strong corrosiveness. RSI was more sensitive than AI although they showed similar tendencies in terms of corrosiveness.

4. Conclusions

In this study, all 12 WTPs in Korea were divided into four regions, namely the Han, Geum, Nakdong, and Yeongsan River basins. The findings from analysis of the rainfall patterns in each of these regions show that the rainfall was four times greater in the rainy season compared with the dry season in each river basin. The greatest difference was found in the Han River basin and the smallest difference was in the Geum River basin. In the Nakdong and Yeongsan River basins, the rainfall only showed a significant increase in July and August, in contrast to the summer rainfall patterns in the Han and Geum River basins.

There are various factors that affect corrosion in the water supply pipes: pH, water temperature, TDS, Ca hardness, and alkalinity. These factors define the strength of corrosion based on the surrounding environment. The sensitivity of LSI, RSI, and AI to these corrosion factors was analyzed. pH appeared to have the greatest influence on the corrosion indices, with sensitivity analysis showing a value of 0.1 for LSI and AI, and a value of −0.1 for RSI. It can be concluded that pH had the greatest effect on the corrosion indices, compared with the other corrosion factors of alkalinity, Ca hardness, temperature, and TDS.

Changes in the corrosion indices as a result of increased rainfall during the rainy season were also examined. The addition of excessive amounts of coagulant and liquefied chlorine during the water treatment process reduces the pH level, with the corresponding change in the LSI value describing strong corrosiveness. LSI of the Nakdong River basin showed strong corrosiveness with a value of LSI −2.94 at a pH value of 6.60. Alkalinity concentrations were also examined and showed a reduction in all four river basins during the rainy season, a similar pattern to that shown for pH values. An alkalinity concentration of 10.58 mg/L in the Nakdong River basin corresponded with strong corrosiveness levels with LSI −2.94.

Unlike pH and alkalinity, Ca hardness did not show any noticeable change during the rainy season across the four river basins. The Ca hardness concentration of 23.14 mg/L in the Nakdong River basin was associated with strong corrosiveness (LSI = −2.94).

The characteristics of corrosion indices in each river basin have been examined by comparing and analyzing LSI, RSI, and AI. A number of conclusions can be drawn from these findings. First, when comparing LSI and RSI, the LSI values of the Han and the Geum River basins show medium corrosiveness, whereas the RSI values in both rivers show strong corrosiveness. Both LSI and RSI in the Nakdong River basin show strong corrosiveness, with values of −2.94 and 12.53, respectively. Second, when comparing and analyzing LSI and AI, both corrosion indices in the Han and the Geum River basins show medium corrosiveness, whereas LSI and AI in the Nakdong and the Yeongsan River basins show strong corrosiveness. RSI was more sensitive than AI although they showed similar tendencies in terms of corrosiveness.

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