



Assessment of Corrosion Potential Based on Water Quality Index in the Distribution Network of Urban Patna, Bihar, India

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ABSTRACT

Corrosion in the distribution network pipe can lead to pipe failure and water quality problems. This study assesses the corrosion or scaling potential based on the Water Quality Index (WQI) of drinking water in the distribution networks of Patna, Bihar, India. The water samples were collected from 18 points of the distribution network. In situ parameters like temperature, pH, electrical conductivity, and TDS were measured. Other parameters such as Alkalinity, Total hardness, Calcium, Magnesium, Chloride, Residual chlorine, Sulfate, Nitrate, and Dissolved oxygen were examined in the laboratory. Corrosiveness indicators, such as the Langelier saturation index (LSI), Ryznar stability index (RSI), Puckorius scaling index (PSI), Larson-Skold index (Ls), and Aggressive index (AI) are being used for water sample corrosion prediction. Experimental Corrosion rate (CR) is analyzed to show the actual prediction of corrosion. WQI was calculated to observe the effect of water quality on Corrosiveness indices and CR. A general conclusion was reached that LSI concludes 66.67% corrosive, 22.22% scaling, and 11.11% neutral, RSI concludes 88.88% corrosive, 5.56% scaling, and 5.56% neutral, PSI indicates 38.88% corrosive, 5.56% scaling, and 55.56% neutral, Ls indicates 94.44% scaling, and 5.56% corrosive, AI indicates 77.78% corrosive, and only 22.22% scaling. The average Experimental Corrosion rate is found at 1.91 mils per year. In this study, a weak correlation ($r = 0.35$) between Corrosion rate and WQI has been observed. A weak correlation is also observed between corrosion rate and corrosiveness indices ($r < 0.5$). It is concluded that the Corrosiveness Indices fail to represent the actual behavior of water.

INTRODUCTION

Corrosion in the pipeline of the distribution network can impact water quality, infrastructure performance, structural integrity, and scaling. Many water quality problems are caused by internal corrosion of distribution network piping and home plumbing, including health concerns, discoloration, and smell (AWWA 2011). A corroded cast iron pipe may produce rusted water or reddish water due to ferric iron (FeIII) (Khiari 2002). Corrosion of cast iron may also produce musty tastes and odors (Kirmeyer & Passarelli 2000). Pipe and valve failures are often caused by corrosion of distribution network piping. A change in the quality of the distribution water can cause red water, an increase in lead or copper concentration in tap water, or other issues (Mirzabeygi et al. 2016). The Water Quality Index of any particular field or particular source may be ascertained by applying water quality parameters which are chemical, physical, and biological parameters (Singh & Kumar 2022). The value of these parameters is risky for human health if the quantity of the parameter exceeds the permissible limits (Kumar & Singh 2021).

Many indices have been developed, but none have been able to quantify and predict the corrosive or scaling effects of water. They can only provide a rough indication (Rossum & Merrill 1983). These are the two common methods of calculating the stability of water: the Langelier saturation index (LSI) and the Ryznar stability index (RSI). In terms of the calcium carbonates scale, LSI and RSI are designed as predictive tools. Scales such as those containing calcium phosphate, calcium sulfate, silica, and magnesium silicate cannot be estimated using these techniques (Alsaqqar et al. 2014). Other tools are used as the Puckorius scaling index (PSI), Aggressive index (AI), and Larson-Skold index (Ls).

These indices are derived using numerical equations. In the case of drinking water, numerical equations have not yet been developed to accurately calculate corrosion. In distribution systems, there are so many factors that contribute to corrosion that these indices are limited (Slavíková et al. 2013). Many factors affect a given Corrosion environment, including dissolved oxygen, pH, temperature, alkalinity, hardness, suspended solids, organic matter, ammonia, specific anions (phosphoric acid, nitrite, sulfate, and

chloride), and biological slimes (EPA 1984). The indices used as LSI, RSI, PSI, Ls, and AI are however dependent upon the seven factors such as pH, temperature, total dissolved solids, calcium hardness, alkalinity, chloride, and sulfate (Kumar et al. 2022). It is, therefore, necessary to monitor corrosion with a direct method such as the corrosion weight loss method.

The objective of this study is to assess the corrosion and scaling potential of the Patna water supply distribution network based on the water quality index (WQI). Along with, demonstrating how changes in water quality can impact corrosion potential. The focus of this study is also on analyzing corrosion potential and comparing it to experimental analysis of corrosion rate.

MATERIALS AND METHODS

Study Area

The study area is Patna urban distribution network, located at N and E. Fig. 1 shows the study area and the sampling points of the water supply distribution network. A total of 18 sampling points were selected. The location of sampling points was S1- Sumitra Nagar, S2- Gurudwara, S3- Old City Court, S4- Gandhi Maidan, S5- Near Sadaqat Ashram, S6- Digha, S7- Danapur, S8- Near Paras Hospital, S9- Rajbanshi Nagar, S10- Patna Station, S11- Rajendra Nagar, S12- Kadamkuna, S13- Chitkohra, S14- Phulwari Sharif, S15- AIIMS Patna, S16- Mithapur Farm Area, S17- Kumhrar, S18- Begampur.

Sample Collection

The sampling procedure was followed using the methods described in the Standard method (APHA 1989). The water samples were collected from 18 different points of the distribution network from October to November 2021. Polyethylene bottles with a capacity of 2 liters were used to collect the samples. The bottles were sealed tightly so that no leakage would occur and stored at 4°C in a dark, dry place within 3 h of collection.

Determination of Physicochemical Parameters

All experiment was followed using the method described in the standard method (APHA 1989). A pH probe tester pen was used to measure the pH on a site. (Eutech instrument cyberxan CON11) was used to measure temperature, conductivity, and TDS at a site. A titration method was used to examine total hardness, calcium hardness, magnesium hardness, and alkalinity. The concentration of chloride was determined by the argentometric method. Nitrate and Sulfate were analyzed using UV Spectrophotometers (220 & 275 nm for Nitrate and 420 nm for Sulfate). Winklers method (iodometric method) was used to measure Dissolved Oxygen using an oxidation-reduction titration method. A method of iodometric titration was used to measure residual chlorine.

Determination of Corrosion Potential

The corrosion potential of water samples was determined using the indicators LSI, RSI, PSI, Ls, and AI. These indices are calculated using seven physicochemical parameters

Table 1: Mathematical Equations and classification of Corrosiveness indices.

Index	Equation	Index value	Water condition
Langelier Saturation Index (LSI)	$LSI = pH - pH_s$ $pH_s = (9.3 + A + B) - (C + D)$ $A = (\text{Log (TDS)} - 1) / 10$ $B = -13.2(\text{Log } (^{\circ}\text{C} + 273)) + 34.55$ $C = \text{Log } (\text{Ca}^{++} + \text{CaCO}_3)$ $D = \text{Log } (\text{Alkalinity as CaCO}_3)$	LSI < 0	Corrosion occurs
		LSI = 0	Neutral
		LSI > 0	Scaling occurs
Ryznar Stability Index (RSI)	RSI = 2pHs - pH	RSI < 5.5	High scale forming
		5.5 < RSI < 6.2	Low scale-forming
		6.2 □ RSI □ 6.8	Neutral
		6.8 < RSI < 8.5	Low corrosive
		RSI □ 8.5	High corrosive
Puckorius Scaling Index (PSI)	$PSI = 2pH_s - pH_{eq}$ $pH_{eq} = 1.465 \log (\text{Alkalinity}) + 4.54$	PSI > 7	Corrosion occurs
		PSI < 6	Scaling occurs
Larson-Skold Index (Ls)	$Ls = (C_{Cl^-} + C_{SO_4^{2-}}) / (C_{HCO_3^-} + C_{CO_3^{2-}})$ C = Concentration in mg.L ⁻¹	Ls > 1.2	Greater corrosion rate
		0.8 □ Ls □ 1.2	High corrosion occurs
		Ls < 0.8	Scaling occurs
Aggressive Index (AI)	AI = pH + log ((Ca ⁺⁺) (Alkalinity))	AI < 10	Corrosion occurs
		10 □ AI □ 12	Moderately corrosive
		AI > 12	Scaling occurs

pH = Actual, pH_s = Saturated pH, pH_{eq} = Equivalent pH

including pH, Temperature, TDS, Alkalinity, Calcium hardness, Chloride, and Sulfate. Corrosiveness indices are presented in Table 1 (Acharya et al. 2018, Alimoradi et al. 2018, García-Ávila et al. 2018).

Determination of Corrosion Rate

The method described in ASTM G1 was used for the determination of the corrosion rate (ASTM G1-90 1999). Galvanized iron (GI) specimens were used as test coupons. The size of the test coupon was 25 mm 17.9 mm 1.5 mm. The test coupon had been precleaned using the corrosion cleaning reagent. It was a mixture of Hydrochloric acid (500 mL) and Hexamethylene tetramine (3.5 g) and made to 1000 mL in distilled water. Further, the test coupon was washed followed by distilled water, acetone, and distilled water. The initial weight of the dried test coupon was measured with an accuracy of 0.0001 g. Then the test coupon was immersed in the 300 mL test sample of water for 30 days. After the completion of the period test coupons were taken from the test water sample. Cleaning procedures were repeated as initial then final weighing was taken. Eq. (1) of corrosion rate in mils per year (MPY) is given as follows (EPA 1984):

$$\text{Corrosion rate (MPY)} = \frac{K W}{DAT} \quad \dots(1)$$

Where

W = Weight loss (mg)

D = Density of specimen (g.cm⁻³)

A = Surface Area (inch²)

T = Time period (hours)

K = Constant (534)

Determination of Water Quality Index (WQI) (Brown et al. 1970)

The method described by (Brown et al. 1970) was used for the determination of the water quality index. A total of 10 parameters were used for the calculation of WQI including pH, TDS, Alkalinity, TH, Calcium, Magnesium, Sulfate, Chloride, Nitrate, and DO. Determination of WQI was a three steps process.

In the first step Water Quality Rating (Qi) was determined using Eq. (2) given below:

$$Q_i = \frac{[X_a - X_i]}{[X_s - X_i]} \times 100 \quad \dots(2)$$

Where,

Qi = Water quality rating of the parameter

Xa = Calculated value of the water quality parameter

Xi = Ideal value of a parameter

Xs = Standard permissible value for the water quality parameter

In the second step, Relative Unit Weight was determined using Eq. (3).

$$W_i = \frac{K}{X_s} \quad \dots(3)$$

Where,

Wi = Unit weight for the parameter

Xs = Standard permissible value of the parameters

K = Proportionality constant

The proportionality constant (K) was determined using Eq. (4).

$$K = \frac{1}{\sum X_s} \quad \dots(4)$$

Where,

Xs = Standard permissible value of the parameters.

In the third step, Water Quality Index was determined using Eq. (5).

$$WQI = \frac{\sum W_i Q_i}{\sum W_i} \quad \dots(5)$$

Where,

Wi = Unit weight for the parameter

Qi = Water quality rating of the parameter

Statistical and Graphical Analysis

Microsoft Excel office 2019 is used for statistical analysis. QGIS 3.14 is used to create a map of the study area and sample locations. Statistical correlation of corrosion rate with indices is calculated using the IBM SPSS Statistics version 28.

RESULTS AND DISCUSSION

The Technique Used for the Selection of the Study Area

As there is no map available of the distribution network (Patna), the main roads of Patna were assumed to be the layout of the distribution network. The samples were collected at a distance of 4 to 6 km beside the main road (Fig. 1). The Physicochemical analysis is shown in Table 2.

Physicochemical Parameters Analysis

Physicochemical results were compared to drinking water standards as provided by the (BIS 2012) mentioned in Table 3. Water temperature was found in the range of

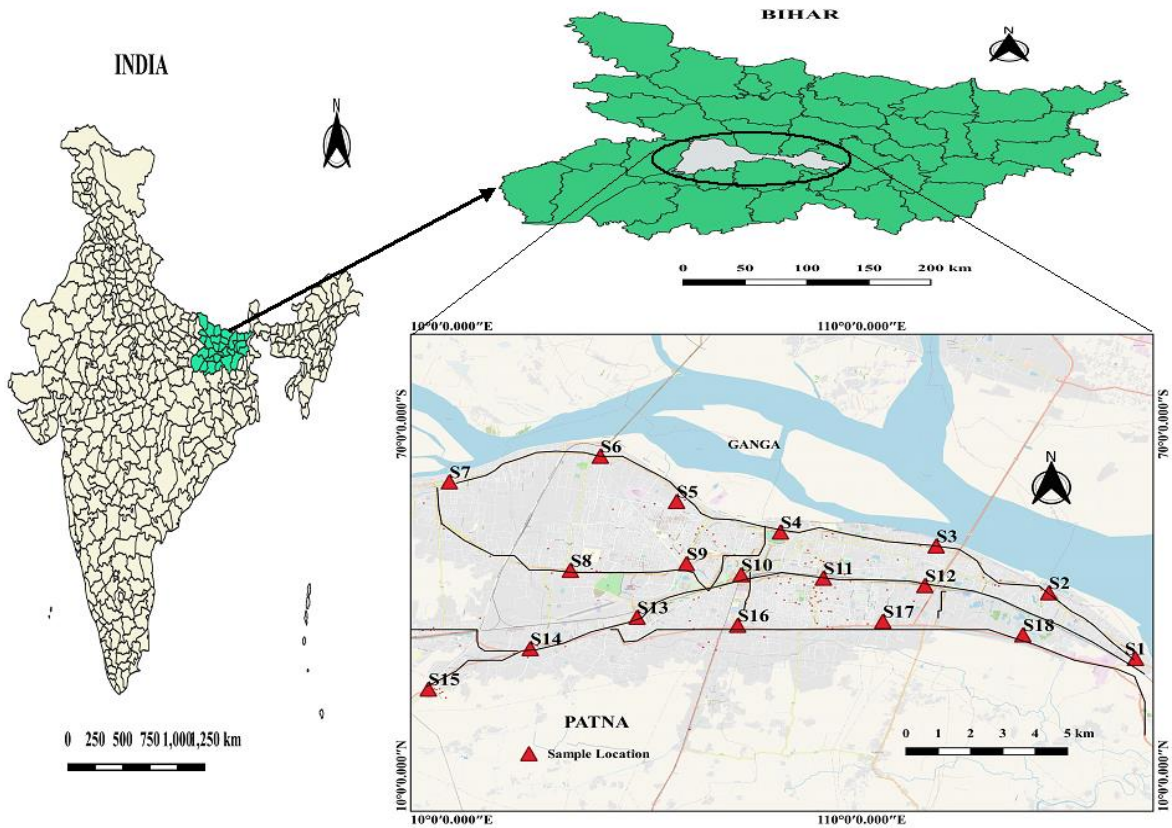


Fig. 1: Study area and sampling points.

Table 2: Physicochemical analysis of the samples.

Sample No.	TDS mg.L ⁻¹	Temp. °C	Cond. µS/cm	pH	Alkalinity mg.L ⁻¹	TH mg.L ⁻¹	Ca ²⁺ mg.L ⁻¹	Mg ²⁺ mg.L ⁻¹	Cl ⁻ mg.L ⁻¹	SO ₄ ²⁻ mg.L ⁻¹	NO ₃ ⁻ mg.L ⁻¹	DO mg.L ⁻¹
S1	733	23.3	1033	7.48	176	256	152	104	36	37	0	4
S2	765	23.4	1078	7.48	184	280	192	88	44	76.30	0	3.4
S3	2180	23.6	3080	7.15	492	664	560	104	140	385	13	3.4
S4	578	22.8	815	7.19	324	296	180	116	44	96.45	0.3	4.8
S5	619	25.4	874	7.38	328	80	40	40	40	10.70	0	4
S6	663	25.6	948	7.59	376	56	30	26	24	7.80	0.8	4
S7	1240	25.2	1736	7.32	568	80	50	30	120	84.80	11	4
S8	646	25.3	909	7.67	328	48	40	8	40	8.40	0.2	3
S9	708	25.2	995	7.38	304	64	40	24	152	12.24	0.5	2.8
S10	565	24.6	796	6.95	200	240	144	96	20	12.50	0	5.2
S11	415	24.4	586	7.45	300	300	200	100	60	41.50	1.8	5.2
S12	540	24.3	767	7.30	280	300	240	60	130	57.50	0.2	4.6
S13	727	24.2	1032	6.81	240	336	216	120	44	33	0	3
S14	696	24.2	982	6.98	200	256	160	96	40	19.50	0.7	5.4
S15	495	24.6	697	7.02	160	248	160	88	20	16.50	0	5.4
S16	643	22.5	910	7.05	320	328	176	152	28	34.57	0.1	5.2
S17	611	23.3	890	6.98	340	336	196	140	60	117.61	0.7	4.2
S18	592	23.6	830	7.47	360	260	196	64	74	17.24	0.5	4

TDS = Total dissolved solid, Temp.=Temperature, Cond.=Conductivity, TH = Tota hardness, DO = Dissolved oxygen

22.5 to 25.6°C. The range is not defined by WHO or BIS, however, the temperature of the water has an impact on the chemical and biological quality. As temperatures increase, corrosion reactions also increase. Therefore, hot water is more corrosive than cold water (EPA 1984). Each of the water samples showed a pH between 6.5 and 8.5 (BIS 2012). Corrosion rates increase with a lower pH value. pH values above 7.0 enhance scaling and protect the pipe (EPA 1984). Only S3 (Old City Court) and S7 (Danapur) exceeded the permissible limit (WHO 2006) for electrical conductivity. The limit of Electrical Conductivity (EC) is not defined by the (BIS 2012). The total dissolved solids in 16 water samples exceeded the permissible limit set by BIS (500 mg.L⁻¹ as CaCO₃). Water samples S11-Rajendra Nagar (415 mg.L⁻¹) and S15-AIIMS Patna (495 mg.L⁻¹) had TDS within the range. Electrical conductivity increases as TDS increases. The electrochemical circuit is completed by water when the EC increases. As a result, it generates a corrosive current (EPA 1984). Alkalinity concentrations in 15 water samples exceeded the (BIS 2012) permissible limit (200 mg/L as CaCO₃). The highest alkalinity is 492 mg.L⁻¹ as CaCO₃ in water sample number S3 (Old city court). Alkalinity produces CaCO₃ coatings on pipe surfaces. Hardness levels in 13 water samples exceeded the permissible limit (200 mg.L⁻¹ CaCO₃) specified by (BIS 2012). Hardness levels in samples S5, S6, S7, S8, and S9 fell within acceptable ranges. Sample number S3 (Old city court) had the highest hardness value of 664 mg.L⁻¹. The hardness of water is classified into soft water (<75 mg.L⁻¹ as CaCO₃), slightly hard water (75-150 mg.L⁻¹ as CaCO₃), moderately hard water (150-300 mg.L⁻¹ as CaCO₃), and very hard water (>300 mg.L⁻¹) (Tyagi & Sarma 2020). Hard water is generally less corrosive than soft water (EPA 1984). Hardness is classified into carbonate hardness (Due to CO₃²⁻ and HCO₃⁻) and non-carbonate hardness (Due to Cl⁻, NO₃⁻, SO₄²⁻ etc.). Carbonate hardness was found in all water samples. Non-carbonate hardness was found in 9 water samples. Carbonate hardness is called temporary hardness. Non-carbonate hardness is called permanent hardness. Softening is done to remove the hardness from water both temporary and permanent hardness. The Lime soda process and Zeolite process have used the removal of the permanent hardness (Tchobanoglous et al. 2003). The range of carbonate hardness was found 48-492 mg.L⁻¹ and non-carbonate hardness was 0-172 mg.L⁻¹. It was found that 16.67% of water samples have fallen under soft water and 11.11% of water samples lie in slightly hard water and 50% of water samples lie in moderately hard water and 22.22% of water samples fell in very hard water. Calcium hardness was found to be higher than 75 mg.L⁻¹ in 13 of the water samples (BIS 2012), while calcium hardness was within safe limits in water samples S5, S6, S7,

S8, and S9. Calcium hardness was highest at 560 mg.L⁻¹ in water sample number S3 (Old city court). Calcium helps to reduce corrosion by forming a protective CaCO₃ layer (EPA 1984). In 14 water samples, magnesium hardness was greater than (30 mg.L⁻¹ as CaCO₃) permissible limit defined by (BIS 2012). Mg hardness in water samples S6, S7, S8, and S9 was within the range. The chloride concentration in all water samples was found within the permissible limit (200 mg.L⁻¹) prescribed by (BIS 2012). Similarly, the sulfate concentration in all 17 samples was within the limit described by (BIS 2012). Sample number S3 (Old city court) contained the largest amount of sulfate. Chloride is three times more affinity than sulfate (EPA 1984). Nitrate levels were found within a permissible range (45 mg.L⁻¹) prescribed by the (BIS 2012). Nitrate is an indicator of organic matter. The presence of organic matter, directly and indirectly, affects the corrosion rate. It may increase or decrease the corrosion rate (EPA 1984). Water sample numbers S10, S11, S14, S15, and S16 contain more than 5 mg.L⁻¹ of dissolved oxygen, and the other samples contain less than 5 mg.L⁻¹. A higher level of Dissolved Oxygen in the pipeline increases its corrosion rate. However, a lower level indicates microbial activity (EPA 1984). No residual chlorine was found in any samples, indicating a lack of disinfection.

Corrosion Potential of Water Samples

Langelier Saturation Index (LSI)

LSI and RSI are the main predictors of the corrosiveness of water (Pisigan & Singley 1985). LSI incorporates a useful indicator for corrosive water in its indices. LSI can be defined as the difference between the actual pH of the water and the calculated pH as follows: $LSI = pH_{actual} - pH_{calculated}$ (Langelier 1936). LSI of water samples is given in Fig 2. (a) and corrosive behavior is mentioned in Table 4. This index measures the formation and scale-out of calcium carbonate from water. It is based on pH. $LSI < 0$ indicates the corrosive potential of water and $LSI > 0$ indicates the scaling potential of water. LSI of sample number S2 (Gurudwara) was almost zero (0.02). LSI of sample number S4 (Gandhi Maidan) was also nearly zero (-0.05). These water samples exhibit neither scaling nor corrosive tendency of water. LSI of sample number S3 (Old City Court) was found a maximum value of 0.54. It exhibits the scaling tendency of water due to the high value of TDS, Alkalinity, and Ca hardness. LSI of sample number S10 (Patna Station) was found a minimum value of -0.56. It exhibits a corrosive tendency of water due to slightly acidic (pH = 6.95) in nature. The mean value of LSI was -0.17 which represents the corrosive tendency of water. LSI represents 66.67% of water samples Corrosive, 22.22% Scaling, and 11.11% Neutral.

Table 3: Descriptive statistics of water quality parameters with limits specified by (BIS 2012).

Variable	Minimum	Maximum	Mean	Standard Deviation	BIS
Temperature (°C)	22.50	25.60	24.19	0.93	-
pH	6.81	7.67	7.26	0.25	6.5-8.5
Conductivity (µS/cm)	586.00	3080.00	1053.22	558.09	-
TDS (mg/L)	415.00	2180.00	745.33	396.07	500
Alkalinity (mg/L as a CaCO ₃)	160.00	568.00	304.44	106.91	200
TH (mg/L as a CaCO ₃)	48.00	664.00	246.00	147.75	200
Ca Hardness (mg/L as a CaCO ₃)	30.00	560.00	165.11	120.65	75
Mg Hardness (mg/L as a CaCO ₃)	8.00	152.00	80.89	41.90	30
Chloride (mg/L)	20.00	152.00	62.00	43.08	250
Sulfate (mg/L)	7.80	385.00	59.37	87.82	200
Nitrate (mg/L)	0.00	13.00	1.65	3.81	45
DO (mg/L)	2.80	5.40	4.20	0.87	>5

Ryznar Stability Index (RSI)

RSI is defined as the difference between the calculated pH and actual pH of water, as follows: $2 \times \text{calculated pH} - \text{actual pH}$ (Ryznar 1944). RSI of water samples is given in Fig 2. (b) and corrosive behavior is mentioned in Table 4. This index measures the formation and scale-out of calcium carbonate from water. It is based on pH. RSI is a modification of the LSI which has higher accuracy than LSI. RSI exhibits neutral in the range of 6.2 to 6.8. The RSI of sample number S18 (Begampur) was nearly 6.8 (6.82). It exhibits neither scaling nor the corrosive tendency of water. RSI of sample number S3 (Old City Court) was a minimum value of 6.07. It was found in the range of 5.5 to 6.2 which represents low-scale forming. All water samples except S3 and S18 had RSI values between 6.8 and 8.5, indicating that they have low corrosive potential. The mean value of RSI was found at 7.59 representing the low corrosive tendency of water. The result of RSI indicates that 88.88% of water samples are low corrosive, 5.56% low scaling, and 5.56% neutral. In comparison to LSI, RSI indicates more corrosive, less scaling, and less neutral.

Puckorius Scaling Index (PSI)

The Puckorius Scaling Index indicates a greater accumulation of sediments created in equilibrium due to the buffer capacity (Taghipour et al. 2012). The mathematical equation of PSI is derived to replace the actual pH in the equation of LSI and RSI with the equilibrium pH. PSI of the water samples is shown in Fig 2. (c) and corrosive behavior is mentioned in Table 4. $PSI < 6$ represents the scaling tendency of water and $PSI > 7$ represents the corrosive tendency of water. PSI of sample number S3 (Old City Court) was a minimum value of 4.73. It exhibits the scaling tendency of water. PSI of sample numbers S2 and S14 were nearly 7 (7.06 & 7.05) representing

neither scaling nor corrosive. Otherwise, the PSI of sample numbers S4, S7, S11, S12, S13, S16, S17 & S18 lie in the range of 6 to 7 representing the neutral behavior of water. PSI of water samples S1, S5, S6, S8, S9, S10 & S15 were found greater than 7. These are representing the corrosive behavior of water. The mean value of PSI was 6.71 which indicates neither scaling nor corrosive tendency of water. PSI indicates that 38.88% of water samples are Corrosive, 5.56% Scaling, and 55.56% Neutral.

Larson-Skold Index (Ls)

RSI is a corrosion rate indicator tool for steel and cast iron pipes that are modified by Larson-Skold (Larson & Skold 1958). The mathematical equation of Ls is derived by the use of parameters such as the concentration of chloride, sulfate, carbonate, and bicarbonate alkalinity. $Ls < 0.8$ represents the scaling tendency of water, $0.8 < Ls < 1.2$ represents the corrosion tendency of water, and $Ls > 1.2$ represents a greater corrosion rate. Ls of water samples are shown in Fig 2. (d) and corrosive behavior is mentioned in Table 4. A low value of chloride and sulfate was detected in all water samples except S3, which indicates the scaling tendency of water. A corrosion tendency was found for sample number S3 (Old City Court). This is due to the high levels of chloride and sulfate in the sample. The mean value of Ls was found 0.38 which represents the scaling tendency of water. Ls value indicates 5.56% of water samples are highly corrosive and 94.44% was scaling tendency.

Aggressive Index (AI)

An aggressive index is used to detect corrosion in asbestos-cement pipes (Taghipour et al. 2012). It is a useful indicator for the selection of materials or treatment for corrosion control. The equation of AI is derived by the use of

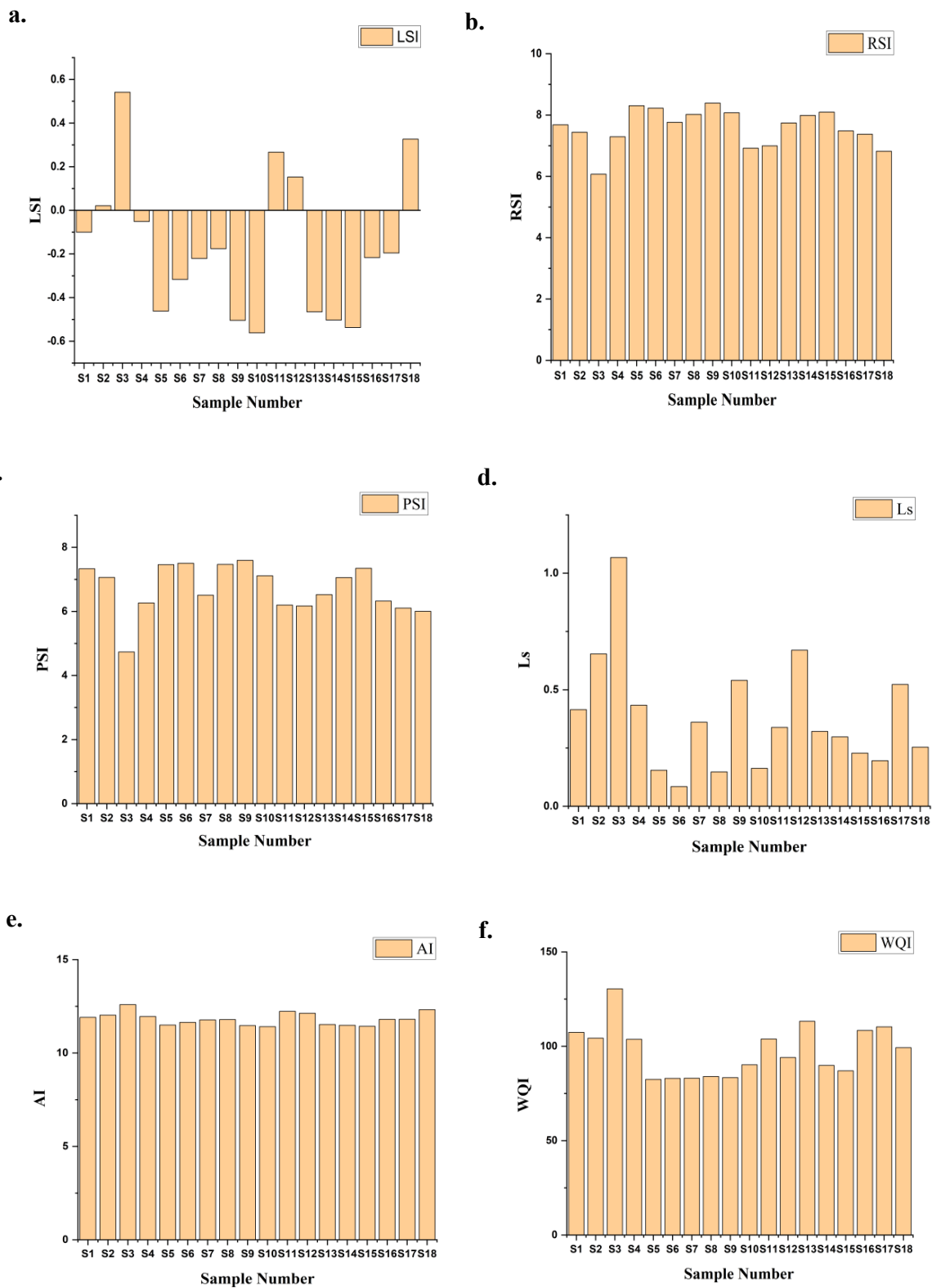


Fig 2: Represents Corrosiveness indices and WQI (a) LSI, (b) RSI, (c) PSI, (d) Ls, (e) AI, (f) WQI.

Table 4: Corrosive behavior and quality status of water samples.

S. No.	LSI	RSI	PSI	Ls	AI	WQI
S1	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	NUD
S2	Neutral	Low corrosive	Neutral	Scaling	Moderately Corrosive	NUD
S3	Scaling	Low Scaling	Scaling	High Corrosive	Scaling	NUD
S4	Neutral	Low corrosive	Neutral	Scaling	Moderately Corrosive	NUD
S5	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S6	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S7	Corrosive	Low corrosive	Neutral	Scaling	Moderately Corrosive	WWQ
S8	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S9	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S10	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S11	Scaling	Low corrosive	Neutral	Scaling	Scaling	NUD
S12	Scaling	Low corrosive	Neutral	Scaling	Scaling	WWQ
S13	Corrosive	Low corrosive	Neutral	Scaling	Moderately Corrosive	NUD
S14	Corrosive	Low corrosive	Neutral	Scaling	Moderately Corrosive	WWQ
S15	Corrosive	Low corrosive	Corrosive	Scaling	Moderately Corrosive	WWQ
S16	Corrosive	Low corrosive	Neutral	Scaling	Moderately Corrosive	NUD
S17	Corrosive	Low corrosive	Neutral	Scaling	Moderately Corrosive	NUD
S18	Scaling	Neutral	Neutral	Scaling	Scaling	WWQ

WWQ-worst water quality, NUD-Not used for drinking

parameters such as calcium hardness, pH, and total alkalinity. AI <10 represents the corrosion tendency of water, $10 < AI < 12$ represents the moderately corrosive behavior of water, and $AI > 12$ represents the scaling tendency of water. AI of water samples is given in Fig 2. (e) and corrosive behavior is mentioned in Table 4. Sample numbers S3, S11, S12 & S18 were found AI greater than 12, which indicates that the water is scaling. AI of the remaining samples ranged from 10 to 12, which indicates a moderately corrosive tendency of the water. The mean value of AI was 11.82 which represents the moderately corrosive tendency of water. AI indicates 77.78% of water samples are moderately corrosive and 22.22% are scaling.

Corrosion Rate Analysis (CR)

Coupon Weight Loss Method was used for corrosion rate analysis. The corrosion rate (30 days) of Galvanised iron specimen is shown in Fig 3. Corrosion rate (CR) has been confirmed that the corrosion has occurred in all samples. The corrosion rate of water samples was lie in the range of 1.31-2.29 MPY. Corrosion rates were highest in water sample 10 (Patna station) and lowest in S14 (Phulwari Sharif). Corrosion-weight loss method only informs about uniform corrosion.

Table 4 illustrates that all the indices have a different

tendency for the same water sample. One index is showing the same water sample to be corrosive, while another index shows scaling or neutral. One index is showing highly corrosive levels for the same water sample, while another index shows low corrosive levels. It is challenging to depict the actual behavior of water samples using these indices. When all the indices give the same result, it is easy to make a decision. The same problem has also been observed in Acharya et al. 2018, Alimoradi et al. 2018, Kalyani et al. 2017, Mirzabeygi et al. 2016, Taghavi et al. 2019, Tyagi & Sarma 2020. The corrosion rate is therefore calculated experimentally to provide strong evidence. It has found less deviation (1.91 MPY).

Water Quality Index Analysis (WQI)

If $Qi = 0$ indicates the absence of pollutants. If $0 < Qi < 100$ indicates the pollutants are in the prescribed range. If $Qi > 100$ indicates the pollutants are above the prescribed range. Water quality rating is divided into five grades i.e., 'A' for best water quality, 'B' for good water quality, 'C' for bad water quality, 'D' for worst water quality, and 'E' for not use for drinking. WQI rating is mentioned in Table 5 (Brown et al. 1970). WQI of the water sample is given in Fig 2. (f) and the quality status of water samples is mentioned in Table 4. The water Quality rating (Qi) of 8 water samples was found

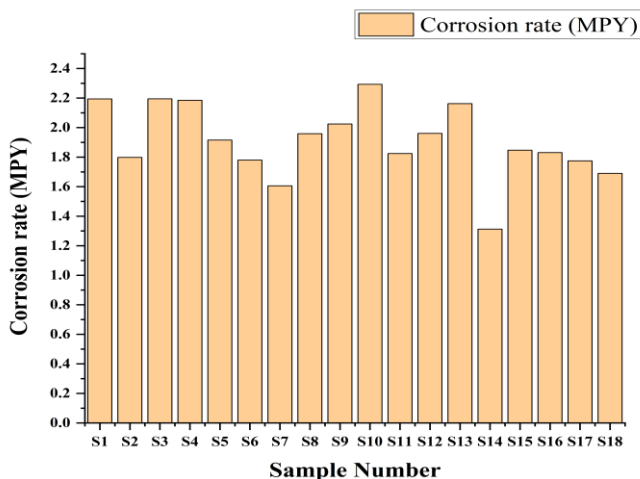


Fig. 3: Represents Corrosion rate of water samples in mils per year.

greater than 100. These indicate the pollutants are above the value of the standards. WQI was found in the range of 82-130. WQI of 8 water samples was found above 100. It means water is not used for drinking purposes graded as 'E'. WQI of the remaining ten water samples lies in the range of 76-100. This indicates the worst water quality is graded as 'D'. The mean value of WQI was found at 97.66 which represents the worst water quality. Overall, the analysis of WQI no sample lies in the range of best water quality zone and good water quality zone. The values of WQI are higher in this study due to excess magnesium and less amount of dissolved oxygen out of ten physicochemical parameters.

Effect of Water Quality on Corrosion Indices and Corrosion Rate

The Pearson Correlation method is used for the indication of correlation presented in Table 6. Pearson correlation mainly explained the relationship between two or more variables. It states weak or strong relationships and directions between two or more variables. Pearson coefficient 'r' indicates a linear relationship between two or more variables (Positive shows the proportional relationship and Negative shows an inverse relationship). If the coefficient of correlation $r < 0.5$ states weakly relates and $r > 0.5$ states strongly relates (Tyagi & Sarma 2020). A weak correlation exists between the experimental Corrosion rate and WQI (Table 6). But Corrosiveness indices are strongly correlated with WQI. WQI is strongly and positively correlated with LSI ($r = 0.594$), & AI (0.63) and strongly and negatively correlated with RSI (-0.776), & PSI (-0.767) at a significant level of $p < 0.01$. It concludes a low quality of water indicates the possibility of scale. High-quality water indicates a corrosive tendency of

water. Ls are strongly and positively correlated with WQI (0.63) at a significant level of $p < 0.01$. It concludes if water quality is excellent, then scaling tendency occurs otherwise corrosive tendency. Water quality follows corrosive or scaling behavior with LSI, RSI, PSI, and AI but is contradictory with Ls. WQI indicates all water samples lie in grade 'D' (Worst water quality) or 'E' (Not used for drinking). Therefore, LSI, RSI, PSI, and AI should indicate the scaling tendency of water, and Ls should indicate the corrosive tendency of water. Practically it is not found in Table 4.

There is a weak correlation exists between corrosion rate and corrosiveness indices ($r < 0.5$) (Table 6). Several studies such as (Kalyani et al. 2017, Pisigan & Singley 1987) also report that the corrosion rate weakly correlates with the corrosiveness index. LSI is strongly and inversely correlated with RSI (-0.924) and PSI (-0.757) both significant at $p < 0.01$. LSI exhibits true relation with RSI and PSI. It concludes as LSI increases whenever RSI or PSI decreases the scaling behavior of water increases. As LSI decreases whenever RSI or PSI increases the corrosive behavior of water increases. LSI is strongly and positively correlated with Ls (0.6) at a significant level of $p < 0.01$. It indicates contradictory results. If LSI increases scaling behavior of water increases whenever Ls increases corrosive behavior of water increases. LSI is strongly and positively correlated with AI (0.998) at a significant level of $p < 0.01$. LSI exhibits true relation with AI. If LSI or AI increases scaling behavior of water increases. If LSI or AI decreases corrosive behavior of water increases. (Kalyani et al. 2017) have told that AI can be used in the place of LSI due to a higher correlation of about 1. Similarly, it has been found that RSI is strongly and positively correlated with PSI (0.927) and negatively correlated with Ls (-0.676), and AI (-0.935) at a significant level of $p < 0.01$. RSI exhibits true relation with PSI and AI and contradictory relation with Ls. PSI is strongly and negatively correlated with Ls (-0.634), and AI (-0.777) both significant at $p < 0.01$. PSI exhibits true relation with AI and contradictory relation with Ls. Ls are strongly and positively correlated with AI (0.625) at a significant level of $p < 0.01$. Ls exhibits contradictory relations with AI. Based on the correlation, LSI, RSI, PSI, and AI should have the same tendency of water but be contradictory to Ls. Practically it is not found in Table 4.

Strategy to Reduce Corrosion Potential in the Water Distribution Network

In this study, pH was found to be nearly acidic and basic. The pH of water plays an important role in its corrosion or scaling behavior. Water quality can be improved using pH adjustment (near neutral pH = 7) using soda ash and sodium

Table 5: WQI rating.

WQI range	water quality rating	Grade
0-25	Best water quality	A
26-50	Good water quality	B
51-75	Bad water quality	C
76-100	Worst water quality	D
Above 100	Not used for drinking	E

bicarbonate. Also, alkalinity and hardness were found to be greater in water that was deposited on the pipe surface. To remove the hardness and alkalinity, a softener or zeolite basin can be used. The most common oxidants such as dissolved oxygen, chlorine, and sulfate can rapidly react with iron pipe and feed the pipe (Zhang et al. 2022). In Patna, the distribution system is mostly cast iron. Therefore, the DO must be controlled and chloride and sulfate are removed from it. A literature review suggests that selecting appropriate materials and designing a distribution system can reduce corrosion. CaCO_3 , inorganic phosphate, sodium silicate, and other chemical inhibitors may be used. These chemicals form a protective film on the surface of a pipe and provide a barrier between the water and the pipe. Corrosion-resistant coatings and paints such as epoxy paint, polyethylene, and coal tar should be used (EPA 1984).

CONCLUSIONS

A general conclusion was reached that LSI concludes 66.67% water sample corrosive, 22.22% scaling, and 11.11% neutral. RSI concludes 88.88% water sample is corrosive, 5.56% scaling, and 5.56% neutral. PSI indicates 38.88% water sample corrosive, 5.56% scaling, and 55.56% neutral. Ls indicates 94.44% water sample scaling, and 5.56% corrosive. AI indicates 77.78% water sample corrosive, and only 22.22% scaling. It has been found all indices give different tendencies of water. Therefore, it is difficult to conclude

whether the tendency of the water sample is corrosive or scaling. That's a reason, experimentally corrosion rate has been found in all water samples. It is observed that the Experimental Corrosion rate is independent of Corrosiveness indices. The average corrosion rate has been found 1.91 MPY. It has been observed that the corrosiveness indices are not able to show the actual behavior of water. In this study, Corrosiveness indices are found not a suitable tool for corrosion monitoring. Dissolved oxygen (DO) influences the corrosion rate but no corrosiveness indices included the DO. The minimum DO is found which may indicate less corrosion rate, may indicate microbial activity. It was also observed that Water quality failed to define the Corrosion rate and tendency of Corrosiveness indices.

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Table 6: Correlation of Corrosion rate (CR) with indices.

	CR	LSI	RSI	PSI	Ls	AI	WQI
CR	1						
LSI	0.075	1					
RSI	-0.118	-0.924^c	1				
PSI	-0.096	-0.757^c	0.927^c	1			
Ls	0.238	0.6^c	-0.676^c	-0.634^c	1		
AI	0.084	0.998^c	-0.935^c	-0.777^c	0.625^c	1	
WQI	0.35	0.594^c	-0.776^c	-0.767^c	0.63^c	0.63^c	1

^cCorrelation is significant at 0.01 level (2-tailed). Bold: $r > 0.5$ indicates a strong correlation.

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