Evaluation of corrosion and scaling tendency indices in a drinking water distribution system: a case study of Bandar Abbas city, Iran

Vali Alipour, Kavoos Dindarloo, Amir Hossein Mahvi and Leila Rezaei

ABSTRACT

Corrosion and scaling is a major problem in water distribution systems, thus evaluation of water corrosivity properties is a routine test in water networks. To evaluate water stability in the Bandar Abbas water distribution system, the network was divided into 15 clusters and 45 samples were taken. Langelier, Ryznar, Puckorius, Larson–Skold (LS) and Aggressive indices were determined and compared to the marble test. The mean parameters included were pH (7.8 ± 0.1), electrical conductivity (1,083.9 ± 108.7 μS/cm), total dissolved solids (595.7 ± 54.7 mg/L), Cl (203.5 ± 18.7 mg/L), SO_4 (174.7 ± 16.0 mg/L), alkalinity (134.5 ± 9.7 mg/L), total hardness (156.5 ± 9.3 mg/L), HCO_3 (137.4 ± 13.0 mg/L) and calcium hardness (71.8 ± 4.3 mg/L). According to the Ryznar, Puckorius and Aggressive Indices, all samples were stable; based on the Langelier Index, 73% of samples were slightly corrosive and the rest were scale forming; according to the LS index, all samples were corrosive. Marble test results showed tested water of all 15 clusters tended to scale formation. Water in Bandar Abbas is slightly scale forming. The most appropriate indices for the network conditions are the Aggressive, Puckorius and Ryznar indices that were consistent with the marble test.

Key words | calcium carbonate, corrosion, scaling, water

Vali Alipour
Kavoos Dindarloo
Leila Rezaei (corresponding author)
Hormozgan Environmental and Occupational Health Engineering Research Center,
Hormozgan University of Medical Sciences,
Bandar Abbas,
Iran
E-mail: *rezael2000@yahoo.com*

Vali Alipour
Kavoos Dindarloo
Department of Environmental Health Engineering
Hormozgan University of Medical Sciences,
Bandar Abbas,
Iran

Amir Hossein Mahvi
School of Public Health,
Tehran University of Medical Sciences,
Tehran,
Iran

INTRODUCTION

Corrosion and scaling are major problems in water distribution systems that may cause economic problems, and hydraulic, aesthetic and health effects (Edwards 2004). Corrosive water can react with household plumbing and metal fixtures resulting in the deterioration of the pipes and increased metal content of the water. Consumption of water with elevated levels of toxic metals, such as lead and copper, has been shown to cause both acute and chronic health problems. In addition, taste and odours, as well as the appearance of delivered water, are adversely affected. The scale could clog or reduce the flow in pipes, cause build-up in hot water heaters and reduce their efficiency, and impart an alkali taste to the water (Demadis 2004, Demadis *et al.* 2007; Edwards 2004).

Factors influencing the release of corrosion scale materials derive from a wide variety of issues associated with water chemistry, biological processes, composition of pipe scale and the hydraulic flow characteristics within the pipe. Chemical properties related to corrosion and scale formation of water include pH, alkalinity, dissolved oxygen content and total dissolved solids (TDS). The main physical characteristics are temperature, flow and velocity of water (Peng *et al.* 2010).

In general two approaches have been used to evaluate the corrosion and scale-forming tendency of water: direct laboratory methods and mathematical indices. The indices include the Langelier saturation index (LSI), Ryznar stability index (RSI), Puckorius scaling index (PSI), Larson–Skold index (LS) and aggressive index (AI) (Omar *et al.* 2010; Slavíčková *et al.* 2013). Details of these indices are presented in Table 1 (Omar *et al.* 2010; Li *et al.* 2012; Lianga *et al.* 2013). As is clear from Table 1, saturated pH, an important factor

doi: 10.2166/wh.2014.157

Table 1 | Corrosion and saturation indices used in the study (Antony *et al.* 2011)

Index	Equation	Index value	Water condition
Langelier saturation index	$LSI = pH - pHs$	$0 > LSI$	Super-saturated, tend to precipitate $CaCO_3$
		$0 = LSI$	Saturated, CaCO is in equilibrium
		$0 < LSI$	Under-saturated, tend to dissolve solid $CaCO_3$
Ryznar stability index	$RSI = 2pHs - pH$	$6 > RSI$	Super-saturated, tend to precipitate $CaCO_3$
		$6 < RSI < 7$	Saturated, CaCO is in equilibrium
		$RSI > 7$	Under-saturated, tend to dissolve solid $CaCO_3$
Puckorius scaling index	$PSI = 2\ (pHeq) - pHs$ $pHeq = 1.465 \times \log10[alk] + 4.54$ $pH = 1.465 + \log(T.ALK) + 4.54$	$PSI < 6$ $PSI > 7$	Scaling is unlikely to occur Likely to dissolve scale
LS index	$LSI = (Cl^- + SO^{2-})/(HCO_3^- + CO_3{}^{2-})$	$LS < 0.8$	Chloride and sulphate are unlikely to interfere with the formation of protecting film
		$0.8 < LS < 1.2$	Corrosion rates may be higher than expected
		$LS > 1.2$	High rates of localized corrosion may be expected.
Aggressive index	$AI = pH + \log[(alk)(H)$	$AI > 12$	Non-aggressive
		$10 < AI < 12$	Moderately aggressive
			Very aggressive

in determining corrosion or scaling of water, is affected by the chemical and physical properties of water given in Table 2.

Among direct methods for measuring corrosion and scale-forming potential in water, the marble test, Enslow test, calcium carbonate precipitation potential (CCPP) and corrosion coupons are the most common. Corrosion coupons are simple and effective tools for the estimation of corrosion rates in water supply systems and can provide a visual indication of the type of the system corrosion. The Enslow test is a continuous version of the alkalinity difference (marble tests): water is fed continuously to a levelling bulb or separator funnel partly filled with $CaCO_3$, the effluent is filtered through crushed marble so that the filtrate is assumed to be in equilibrium with $CaCO_3$. The CCPP equals the change in alkalinity (or calcium) values that occurs during passage through the apparatus (Cheng *et al.* 2010; Kumar *et al.* 2012; Bernats *et al.* 2012). The CCPP is an electrochemical method that measures the electric current produced when dissolved oxygen is reduced on a rotating electrode, and the marble test determines scaling potential of water with precipitated or dissolved amount of lime under selected laboratory conditions (Merrill & Sanks 1979; Nawrocki *et al.* 2010).

Table 2 | Values of (A, B, C and D) for pHs calculation (Dąbrowski *et al.* 2010)

TDS (mg/L)	A	CaH (mg/L $CaCO_3$)[a]	C	Alk (mg/L $CaCO_3$)	D
50–300	0.1	10–11	0.6	10–11	1
400–1,000	0.2	12–13	0.7	12–13	1.1
Temperature (°C)	B	14–17	0.8	14–17	1.2
		18–22	18–22	18–22	1.3
		23–27	23–27	27–23	1.4
		28–34	1.1	28–35	1.5
0–1	2.6	35–43	1.2	36–44	1.6
2–6	2.5	44–55	1.3	45–55	1.7
7–9	2.4	56–69	1.4	56–69	1.8
10–13	2.3	70–87	1.5	70–88	1.9
14–17	2.2	88–110	1.6	89–110	2
18–21	2.1	111–138	1.7	111–139	2.1
22–27	2	139–174	1.8	140–176	2.2
28–31	1.9	175–220	1.9	175–220	2.3
32–37	1.8	230–270	2	230–270	2.4
38–43	1.7	280–340	2.1	280–350	2.5
44–50	1.6	350–430	2.2	360–440	2.6
51–55	1.5	440–550	2.3	450–550	2.7
56–64	1.4	560–690	2.4	560–690	2.8
65–71	1.3	700–870	2.5	700–880	2.9

[a] CaH, calcium hardness.

Various similar formulas have been used to calculate pHs, some of which presented in Equations (1)–(3).

The general equation is:

$$\mathrm{pHs} = \mathrm{T} + \mathrm{S} - \mathrm{Log}[\mathrm{Ca}^{2+}] - \mathrm{Log}[\mathrm{totalalk}] \quad (1)$$

In the LS method, pHs is calculated by Equation (2) (De Zuane 1997).

$$\mathrm{pHs} = \mathrm{A} + \mathrm{B} - \log(\mathrm{Ca}^{2+}) - \log(\mathrm{alk}) \quad (2)$$

where Ca^{2+} is calcium hardness (mg/L as $CaCO_3$) and alk is water alkalinity (mg/L as $CaCO_3$).

This calculation is valid, if pHs is more than 9.3.

In the Langelier saturation index, pHs is calculated by Equation (3).

$$\mathrm{pHs} = (9.3 + \mathrm{A} + \mathrm{B}) - (\mathrm{C} + \mathrm{D}) \quad (3)$$

The city of Bandar Abbas is located in southern Iran and is the capital of Hormozgan province. It has a wet and warm climate. The Bandar Abbas water distribution network (BAWDN) consists of over 800 km of pipes made of asbestos-cement, steel and polyethylene materials.

Due to the importance of corrosion and scaling, several experiments have been carried out for BAWDN by the Bandar Abbas water authorities, but various interpretations have been drawn from the results. The differences assessments of water condition could be due to use of different methods (indices), so there is not a clear description of BAWDN corrosion condition; accordingly this study was conducted to find the most appropriate index to BAWDN condition by using direct and indirect methods.

MATERIALS AND METHODS

Evaluation of water corrosivity and scaling properties was based on physicochemical parameters and stability indices. For this purpose, the BAWDN was divided into 15 clusters (Figure 1), based on divisions of the Bandar Abbas water authority. Three 1 litre samples were taken from each cluster; thus a total 45 samples were collected randomly.

The most current indices LSI, RSI, PSI, LS and AI were evaluated and compared to a direct method, the marble test. The temperature, pH, electrical conductivity (EC), and TDS were determined at the sampling point in the field using an Elmetron CP-501 pH meter and Aqualytic CD24 TDS meter respectively. Analysis for CO_3^{-2}, HCO_3^{-}, hardness and alkalinity was carried out using titration methods and Merck reagents. Sulphate and chloride were measured by using a Hach 2800 spectrophotometer.

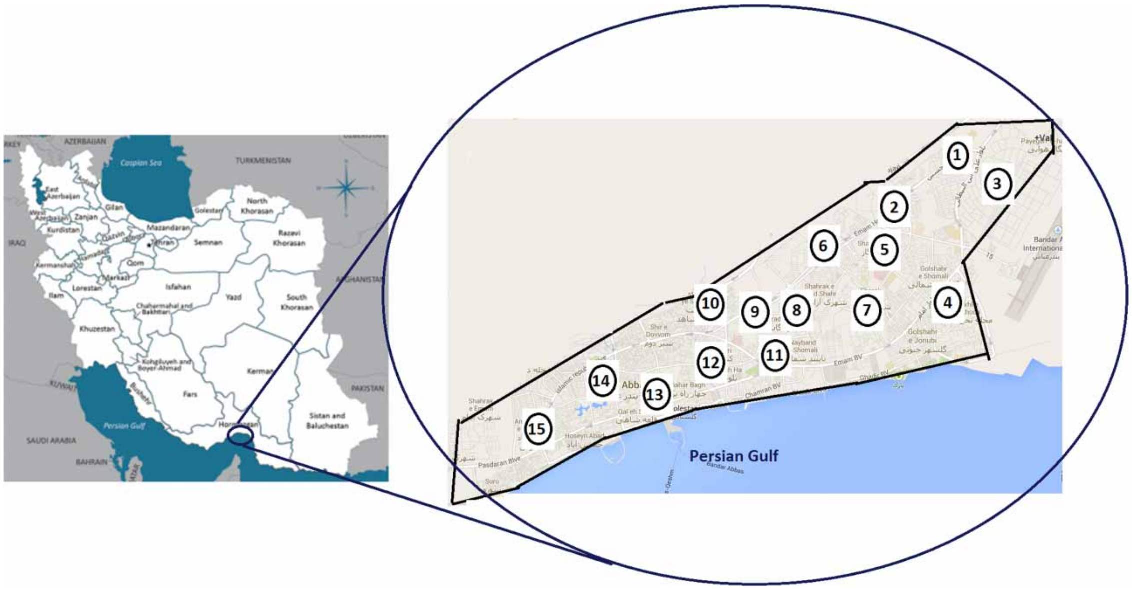

Figure 1 | Location of water sampling sites in Bandar Abbas.

Table 3 | Water quality characteristics associated with corrosion and scaling in BAWDN

Cluster	Sample no.	Temp (°C)	EC (μMoh/cm)	pH	TDS (mg/L)	Cl (mg/L as $CaCO_3$	SO_4 (mg/L)	Alk (mg/L)	TH[a] (mg/L)	HCO_3 (mg/L)	CaH (mg/L)	CaCO3 (mg/L)
1	1	27.5	845	7.97	465	158.88	136.39	112	142.6	112	65.40	54.54
	2	26	813	7.92	448	153.07	131.41	149.2	139.2	111.4	63.84	53.10
	3	27.5	831	8.21	475.5	162.47	139.47	112.4	134.2	112.4	61.55	57.10
2	4	25	1,107.5	7.94	607.5	207.57	178.19	121.2	154.4	112.8	70.82	65.00
	5	25	1,079	8.05	593.5	202.78	174.08	117.6	158	121.4	72.47	67.50
	6	25.5	1,104	8	607.2	207.46	178.10	121.4	149.4	147.2	68.52	70.50
3	7	25.5	1,215	7.63	668.5	228.41	196.08	147.2	176	138	80.72	64.50
	8	26	1,169	7.87	643	219.70	188.60	149.6	171.8	138	78.80	68.00
	9	26	1,161	7.86	638.5	218.16	187.28	137.4	167.4	137.4	76.78	63.50
4	10	23	1,173	7.97	645.5	220.55	189.34	147	167	157	76.59	73.40
	11	22.5	1,171	7.96	644.5	220.21	189.04	150.4	166.5	160	76.36	76.40
	12	23	1,187	7.65	663	226.53	194.47	150	171	161	78.43	75.30
5	13	23.5	1,181.5	7.97	650	222.09	190.66	148	167	158	76.59	77.00
	14	24	1,153	7.77	634.5	216.79	186.11	134.4	168.8	148	77.42	70.10
	15	25	1,063	7.91	588.81	201.18	172.71	137.8	158.18	151.3	72.55	74.60
6	16	25.6	1,019.7	7.6	598	204.32	175.40	144.2	159.432	137.6	73.12	61.30
	17	25.7	957	7.8	615.3	210.23	180.48	150.3	160.3	112.8	73.52	59.00
	18	23.3	1,100	7.7	588.7	201.14	172.68	118.9	158	124.3	72.47	60.30
7	19	24.1	954.3	8.1	611.3	208.86	179.31	154	147.1	115.6	67.47	67.60
	20	25.1	1,002.3	7.7	654	223.45	191.83	135.3	138.3	127.9	63.43	68.20
	21	22.6	1,161	7.65	600.6	205.21	176.17	128.8	144	155.9	66.05	73.30
8	22	22.4	1,173	7.5	498.9	170.46	146.34	119.6	154.6	161.3	70.91	78.55
	23	24.9	1,104	7.8	527.3	180.16	154.67	130.3	160.4	147.2	73.57	71.69
	24	24.2	1,079	8	608.1	207.77	178.37	127.8	159.7	138	73.25	74.21
9	25	24.6	1,000.2	8.04	645	220.38	189.19	148.3	168.1	120.4	77.10	61.63
	26	27.1	960.6	7.65	596.8	203.91	175.05	135.7	138.2	123.9	63.39	63.20
	27	25.6	954.3	7.87	593.1	202.65	173.97	122.2	141.6	135.8	64.94	66.13
10	28	23	1,215	8.03	644.5	220.21	189.04	114.7	135.5	130.5	62.15	67.55
	28	24.3	899.3	7.45	607.2	207.46	178.10	133.4	154.9	151.3	71.04	73.68
	30	22.7	1,153	7.66	475.1	162.33	139.36	127.4	155.6	155.7	71.37	76.10
11	31	23	831	8.21	475.5	162.47	139.47	112.4	167	148	76.59	70.08
	32	24.7	998.1	7.94	607.5	207.57	178.19	121.2	139.4	137.7	63.94	67.06
	33	25	1,079	8.05	417.1	142.51	122.34	117.6	171	137.6	78.43	66.10
12	34	25.5	1,104	8	554.3	189.39	162.59	121.4	167	114.8	76.59	55.91
	35	25.7	1,235	7.63	668.5	228.41	196.08	147.2	168.8	133.3	77.42	58.92
	36	26	1,229	8	643	219.70	188.60	130.6	166	115.6	76.14	55.00
13	37	27.4	1,161	7.65	638.5	218.16	187.28	119.5	157.2	129	72.10	68.82
	38	23.3	1,173	7.5	623.5	213.03	182.88	147	160.3	155.9	73.52	71.92
	39	21.5	1,171	7.96	644.5	220.21	189.04	150.4	158	161.3	72.47	73.55
14	40	23	1,300	7.45	663	226.53	194.47	152	167.4	134.9	76.78	68.70
	41	23.5	1,181.5	7.97	650	222.09	190.66	148	138.3	124.4	63.43	66.58
	42	24.3	1,253	7.77	604.5	206.54	177.31	122.4	150.3	160	68.93	74.50
15	43	25	1,063	7.27	588.81	201.18	172.71	137.8	147.1	151.6	67.47	73.83
	44	26	905.2	7.51	581.5	198.68	170.56	159.6	160.5	145.8	73.61	72.50
	45	27.5	1,107.2	7.86	607.2	207.46	178.10	137.4	158.2	128.5	72.56	69.58

[a] Total hardness.

Table 4 | Statistical parameters for chemical water quality characteristics in BAWDN

	EC (μMoh/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Alk (mg/L)	TH (mg/L)	HCO_3 (mg/L)	CaH (mg/L)
Mean	1,083.9	7.8	595.7	203.5	174.7	134.5	156.5	137.4	71.8
Max	1,244.8	8.1	651.0	222.4	191.0	149.1	171.7	159.3	78.8
Min	829.7	7.5	462.8	158.1	135.8	117.1	138.7	111.9	63.6
St. Dev.	108.7	0.1	54.7	18.7	16.0	9.7	9.3	13.0	4.3

To perform the marble test, two biological oxygen demand bottles (with cork stopper) were used; and two plastic tubes were inserted in the stopper, one for air exhaustion and the other for water discharge; 300 ml of sample water was added to each bottle. The alkalinity test was done using the first bottle immediately. To the second bottle, 0.4 g CaCO3 crystals added and the bottle was placed on shaker (20 rpm; 24 h). By comparing the water alkalinity before and after addition of calcium carbonate, scaling potential of the water was determined; If the first reading is less than the second, water is undersaturated, vice-versa water is corrosive and if both alkalinity readings are equal or very near equal, the water is considered stable (Agatemor & Okolo 2008; Peng *et al.* 2010; Antony *et al.* 2011).

Statistical analysis of data was performed using SPSS 19 for Windows. Correlation coefficient values +1 or −1 between the variables show that there is strong correlation; a value of 0 values no relationship between them. In general, the tested parameters showing correlation coefficient values higher than 0.7 are considered to be strongly correlated whereas values between 0.5 and 0.7 show moderate correlation (Giridharan *et al.* 2008). Pearson product moment correlation coefficients and significant levels of data were calculated to define the correlation between each of the tested parameters of water and indices.

RESULTS

Water quality characteristics of the BAWDN and water stability indices calculations of samples and results of the marble test in each cluster are presented in Table 3.

In order to better explain the above table, statistical data of measured parameters are presented in Table 4.

After evaluating the relevant parameters for corrosion and scaling of water, the five indices were calculated and are presented with the marble test results in Table 5.

As one of the objectives of this study was to compare the common indices to the marble test, the Pearson test was used to investigate the correlation between results of different measurements. Pearson correlation coefficients and significance levels between the marble test and indices indicate that there is no significant correlation (Table 6). So, to evaluate the relationship between marble tests and indices, we compared the percentage of samples with corrosive or scale-forming results as determined by indices and marble tests. Based on the results of the RSI, PSI and AI all samples were stable and showed a slight tendency to scaling, while based on the LSI, 73% of samples were slightly corrosive and the rest showed a slight tendency to scaling, according to the LS, all samples were highly corrosive. The marble test results showed that water of all 15 clusters tended to be scale forming.

DISCUSSION

Based on the results of the present study, all measured chemical parameters of water of BAWDN met the required standards. Results showed that the water in Bandar Abbas is mildly hard (average TH = 156.5 ± 9.3 mg/L as $CaCO_3$) with a good buffering capacity, so this water is generally not corrosive, and this condition is as a result of sufficient alkalinity levels (average total alkalinity = 134.5 ± 9.7 mg/L as $CaCO_3$) and suitable pH (average pH = 7.8 ± 0.1).

Table 5 | Results and interpretation of corrosion[a] of Bandar Abbas drinking water

Index	Clusters														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RSI	7.83	7.80	7.88	7.74	7.85	7.97	8.12	8.03	8.01	8.15	7.80	7.92	7.93	8.07	8.22
	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
LSI	−0.02	−0.02	−0.26	−0.04	−0.15	−0.1	0.17	−0.07	0.04	−0.17	−0.16	0.15	−0.17	0.13	−0.01
	SC	SC	SC	SC	SC	SC	SS	SC	SS	SC	SC	SS	SC	SS	SC
PSI	7.27	7.27	7.58	7.65	7.50	7.51	7.39	7.33	7.39	7.29	7.21	7.40	7.54	7.47	7.53
	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
LS	1.76	2.06	2.03	1.76	1.75	2.06	2.01	1.58	2.06	1.70	1.53	2.20	1.84	1.99	1.79
	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC
AI		12.26	12.18	12.26	12.25	12.04	12.12	12.07	12.16	11.98	12.33	12.22	12.04	12.06	11.90
	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Marble test	1.28	3.15	3.6	3.2	2.78	1.95	2.3	2.15	3.6	3.15	2.35	3.05	3.1	3.25	3.3
	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS

[a] HC, highly corrosive; SC, slightly corrosive; C, corrosive; SS, slight tendency to scale forming; NA, non-aggressive.

Although high concentrations of $SO4^{2-}$ (average = 174.7 ± 16 mg/L) and chloride (average = 203.5± 18.7 mg/L) are present in the water, the influence of hardness and alkalinity was dominant, so that the water has a tendency to scale formation overall.

There were also inequalities among the results of calculated indices and the marble test which may be caused by emphasis of various indices on different parameters of water; for example, the LI provides an indication as to whether a water will precipitate $CaCO_3$ (s) or if it is under-saturated with respect to calcium (Ca^{2+} (aq)) and bicarbonate ($HCO3^-$ (aq)), while the LS emphasises sulphate and chloride concentration.

The recommended value for sulphate and chloride in drinking water is 400 mg/L; the mean values measured for these anions were below the standard, so the two anions cannot be the main reason for water corrosivity.

As a limitation of this study, it should be noted that many factors, such as mineral properties of water, age of water treatment plant structures, dissolved oxygen concentration and environmental temperature, and atmospheric conditions (e.g. precipitation), that could affect the tendency of water to corrosion are not included in the study due to the difficulty of obtaining their values.

The tendency of water to be corrosive or scale forming can be assessed in different ways, but as some direct techniques are costly and time consuming, we are interested in using simpler methods, such as comparative techniques and scaling and corrosion potential indices. Due to the possible different interpretations of various water stability indices, finding the most appropriate index would be helpful in managing water distribution systems to maintain safe drinking water quality.

A study of the potential for scale formation and corrosion of drinking water in south Jordan, showed that based on LSI and RSI values, water samples were slightly corrosive, while based on CCPP values, samples showed no tendency to promote corrosion (Al-Rawajfeha & Al-Shamaileh 2007), thus partially confirming the results of the present study.

Overall, the water of BAWDN is slightly scale forming and among the evaluated indices, the most suitable indices to the BA network condition are AI, PSI and RSI.

Table 6 | Pearson correlation coefficients and significant levels among indices and marble results

		LSI	RSI	PSI	AI	LS	Marble
LSI	*r*		0.963**	−0.029	−0.983**	−0.181	−0.149
	p		0.000	0.850	0.000	0.234	0.327
RSI	*r*	0.963**		−0.258	−0.929**	−0.184	−0.039
	p	0.000		0.087	0.000	0.226	0.799
PSI	*r*	−0.029	−0.258		0.039	0.187	−0.242
	p	0.850	0.087		0.797	0.219	0.109
AI	*r*	−0.983**	−0.929**	0.039		0.208	0.215
	p	0.000	0.000	0.797		0.171	0.157
LS	*r*	−0.181	−0.184	0.187	0.208		−0.164
	p	0.234	0.226	0.219	0.171		0.281
Marble	*r*	−0.149	−0.039	−0.242	0.215	−0.164	
	p	0.327	0.799	0.109	0.157	0.281	

**Correlation is significant at the 0.01 level (two-tailed).

REFERENCES

Agatemor, C. & Okolo, P. 2008 Studies of corrosion tendency of drinking water in the distribution system at the University of Benin. *Environmentalist* **28**, 379–384.

Al-Rawajfeha, A. E. & Al-Shamaileh, E. M. 2007 Assessment of tap water resources quality and its potential of scale formation and corrosivity in Tafila Province, South Jordan. *Desalination* **206**, 322–332.

Antony, A., Gray, S., Childress, A. E., Le-Clech, P. & Leslie, G. 2011 Scale formation and control in high pressure membrane water treatment systems: a review. *J. Membrane Sci.* **383**, 1–16.

Bernats, M., Osterhus, S. W., Dzelzitis, K. & Juhna, T. 2012 Development of an iron pipe corrosion simulation model for a water supply network. *Drink. Water Eng. Sci. Discuss.* **5**, 85–120.

Cheng, R. C., Andrews, T. C., Tseng, T. J. & Wattier, L. K. 2010 Distribution of desalinated seawaters: are corrosion indicators sufficient? *IDA J.* **1**, 24–31.

Dąbrowski, W., Buchta, R., Dąbrowska, B. & Mackie, R. I. 2010 Calcium carbonate equilibria in water supply systems. *Environ. Prot. Eng.* **36**, 75–94.

De Zuane, J. 1997 *Handbook of Drinking Water Quality*, 2nd edn. John Wiley & Sons, New York.

Demadis, K. D. 2004 Focus on operation and maintenance: scale formation and removal. *Power* **148** (6), 17–24.

Demadis, K. D., Mavredaki, E., Stathoulopoulou, A., Neofotistou, E. & Mantzaridis, C. 2007 Industrial water systems: problems, challenges and solutions for the process industries. *Desalination* **213**, 38–46.

Edwards, M. 2004 Controlling corrosion in drinking water distribution systems: a grand challenge for the 21st century. *Water Sci. Technol.* **49** (2), 1–8.

Giridharan, L., Venugopal, T. & Jayaprakash, M. 2008 Evaluation of the seasonal variation on the geochemical parameters and quality assessment of the groundwater in the proximity of River Cooum, Chennai, India. *Environ. Monit. Assess.* **143**, 161–178.

Kumar, S., Suriyanarayanan, A. & Panigrahi, B. S. 2012 Studies on performance of indices in cooling water system. *IJCT* **19**, 75–80.

Li, X. D., Wang, X. S., Ren, H. H., Chen, Y. L. & Mu, Z. T. 2012 Effect of prior corrosion state on the fatigue small cracking behaviour of 6151-T6 aluminum alloy. *Corrosion Science* **55**, 26–33.

Lianga, J., Deng, A., Xie, R., Gomez, M., Hu, J., Zhang, J., Ong, C. N. & Adin, A. 2013 Impact of flow rate on corrosion of cast iron and quality of re-mineralized seawater reverse osmosis (SWRO) membrane product water. *Desalination* **322**, 76–83.

Merrill, D. T. & Sanks, R. L. 1979 Corrosion control by deposition of $CaCO_3$ films: A practical approach for plant operators. *J. Amer. Water Works Assoc.* **70**, 592–634.

Nawrocki, J., Stanisławiak, U. R., Świetlik, J., Olejnik, A. & Sroka, M. J. 2010 Corrosion in a distribution system: steady water and its composition. *Water Res.* **44**, 1863–1872.

Omar, W., Chen, J. & Ulrich, J. 2010 Reduction of seawater scale forming potential using the fluidized bed crystallization technology. *Desalination* **250**, 95–100.

Peng, C. Y., Korshin, G. V., Valentine, R. L., Hill, A. S., Friedman, M. J. & Reiber, S. H. 2010 Characterization of elemental and structural composition of corrosion scales and deposits formed in drinking water distribution systems. *Water Res.* **44**, 4570–4580.

Slavíčková, K., Grünwald, A. & Šťastný, B. 2013 Monitoring of the corrosion of pipes used for the drinking water treatment and supply. *Civ. Eng. Architect.* **1**, 61–65.

First received 14 August 2013; accepted in revised form 26 May 2014. Available online 21 July 2014