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# Potential for iron release in drinking water distribution system: a case study of Hamedan city, Iran

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## ABSTRACT

Blending of water from different sources into an urban drinking water distribution system can have unintended impacts, such as corrosion and/or release of corrosion by-products from pipe surfaces. Hamedan, a city in west Iran, receives water from four different sources that have different physical and chemical characteristics. The potential for iron release from iron distribution pipes due to *in situ* blending of different sources was investigated in this study. A dedicated software was developed to calculate the corrosion indices of different blends expected in different zones of Hamedan's water distribution system. The calculated corrosion indices, and iron release were verified and correlated to actual conditions through water sampling conducted in different zones of the city. The Langelier index (LI), Ryznar stability index (RSI or RI), Puckorius scaling index (PSI), and the calcium carbonate precipitation potential were found to be −0.60 ± 0.30, 8.63 ± 0.57, 8.18 ± 0.34, and −10.95 ± 6.9 mg $CaCO_3$/L, respectively. Alkalinity, pH, and carbonate ion were identified as the important parameters that have a role in the control of iron release. Significant linear correlations of LI, RI, and PSI to iron concentration were observed in samples collected from different zones of the distribution system. The spatial correlation between iron concentration and corrosion indices in different zones of the water distribution system was determined using ordinary Kriging interpolation. These indices indicated a wide variation of corrosive potential in different zones of the distribution system. Therefore, these corrosion indices can be used to estimate, monitor, and minimize the potential for iron release from distribution systems.

*Keywords:* Corrosion index; Drinking water; Iron release; Water distribution system

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## 1. Introduction

Treated potable water is transported from a treatment plant to the consumers tap via water distribution pipelines. The chemical, microbiological, and aesthetic quality of water at the consumer's tap reflects the history of the water and the region from which it originates; the treatment process and chemicals used to treat the water; and the composition, age, and condition of the water distribution pipes [1]. The most common symptom of corrosion problems within a water system is customer complaints with regard to "red water" and "discolored water" [2].

In metallic drinking water pipes, red or colored water is caused by corrosion by-products, such as oxides of iron, zinc, copper, and lead, released from the inner surface of metal pipes [3,4]. The corrosion of metal pipes in the water distribution systems is a complex electrochemical and physicochemical phenomenon between a metal surface and water, which cannot always be eliminated but can usually be controlled in a cost-effective manner [5,6]. Corrosive water can cause problems, such as health hazards, taste, color, and higher utility pumping costs, due to the obstruction of water flow by the corrosion products deposited on the pipe surface in water pipelines and plumbing systems [7,8]. The corrosiveness of the water depends on many chemical factors, such as pH, alkalinity, buffer intensity, dissolved oxygen, and total dissolved solids (TDS); physical properties such as temperature, flow, and velocity; as well as the composition, age, and condition of the pipe [9].

A sensitivity analysis of corrosion indices with varying corrosion factors indicates that pH and alkalinity have a predominant impact on corrosion potential compared to other factors [10,11]. The impact of pH adjustment and phosphate-based inhibitors on iron release in distribution systems was examined by Alshehri et al. [12]. Imran et al. [13] observed that iron release in a pilot distribution system was significantly affected by variations in temperature, alkalinity, chlorides, sulfates, and hydraulic residence time of the blended water. In most water treatment facilities, pH, alkalinity, and calcium hardness are manipulated for corrosion control to prevent internal corrosion in the water distribution system [14,15]. Usually, the corrosion control measures are implemented through statistical, empirical, or mechanistic models (indices) of corrosion potential that are linked to easily amendable water quality parameters such as pH, alkalinity, and calcium hardness [16].

The current study was carried out in Hamedan city in west Iran. Hamedan's drinking water demand is met by four sources that are a mix of surface, ground, and spring sources with different water chemistries [17]. There is no centralized blending provided and the different source waters mix in the distribution system in different blend ratios. Therefore, different zones of the distribution system experience significantly different water chemistry. For instance, relatively low pH and high dissolved oxygen are observed in the Morad-Beik springs in south Hamedan [18]. In sharp contrast, another source (Dasht-e-Bahar's groundwater wells) is high in alkalinity [19]. While lower pH and higher dissolved oxygen can promote iron release, high levels of alkalinity can mitigate iron release by increasing scale formation on pipe surfaces. Thus, in Hamedan's water distribution system, depending on the blend proportions from different sources, the potential for iron release may either reduce or increase.

The purpose of this project is to assess the potential for iron release in drinking water distribution system of Hamedan city using four different corrosion indices (LI, RI, PSI, and CCPP). The project will provide information about the possible causes of corrosion tendency of the water and provide a means of proactive control of water quality in the distribution system using appropriate indices.

## 2. Materials and methods

### 2.1. Study area

Hamedan city (population 548, 378) in west Iran has a total drinking water demand of 130,000 $m^3/d$. This demand is met by four principal water sources:

1. Surface water (25,000–28,000 $m^3/d$) from Ekbatan dam gets treated at the Ekbatan Water Treatment Plant (WTP). The treated water is stored in the Azad reservoir from where it enters the city's distribution system.
2. Surface water (26,000–30,000 $m^3/d$) from Ekbatan dam is mixed with surface water from Abshineh dam (8,700 $m^3/d$) and gets treated at the Shahid-Beheshti WTP. The treated water is stored in the Shahid-Beheshti reservoir and the Omid-e-Ekbatan reservoir for distribution.
3. Groundwater (66,000 $m^3/d$) is pumped from the Dasht-e-Bahar boreholes and stored in the Lona Park reservoir for distribution. There are 26 wells in three groups of boreholes in Dasht-e-Bahar region. The Dasht-e-Bahar boreholes account for 40% of the total water supply of Hamedan.
4. Spring water (2,600 $m^3/d$) from the Morad-Beik springs is stored in the Morad-Beik reservoir for distribution.

The drinking water distribution system of Hamedan city is principally composed of four different pipe materials: asbestos–cement (60%), polyethylene (25%), ductile iron pipe (DIP) (10%), and gray cast iron (GCI) (5%) [20]. At the time of this study, information on the age and location of the pipes was not available. However, according to municipal sources, out of the 1,014 km of piping system in the city, 35% is old and needs to be replaced [21].

### 2.2. Sampling

Water samples were collected from consumer's taps in 10 residential locations spread over Hamedan city. Sampling was done during three months (one sample was collected each month) and then the average values of the water characteristics were used for further analysis. The samples were collected in clean polyethylene bottles, washed with cleaning mixture ($K_2Cr_2O_7/H_2SO_4$), tap water, followed by distilled deionized water obtained with a Millipure water system (Sas 67120 Molshem). Before collection of samples, each bottle was rinsed with the same water thrice and then filled with sample. All samples were stored in an ice bag at a temperature below 4˚C and transferred to the laboratory and the analyses were carried out within 24 h.

### 2.3. Analysis

Temperature, pH, TDS, and electrical conductivity (EC) were measured *in situ* with a HACH Sention 6 multimeter. Turbidimetric and argentometric methods were used for the determination of $SO_4^{2-}$ and $Cl^-$, respectively, and the concentration of iron was determined using phenanthroline method [22]. The samples were analyzed for major components, $Ca^{2+}$ and $Mg^{2+}$ (titration with 0.1 N ethylenediaminetetraacetic acid (EDTA)). The total alkalinity was also measured by titration method with 0.02 N $H_2SO_4$. The concentrations of carbonic acid, carbonate, and bicarbonate were calculated theoretically from the pH and alkalinity data.

### 2.4. Data and analysis

The corrosiveness of tap water was estimated through calculated corrosion indices. Most corrosion indexes, such as the Langelier saturation index (LI) [23], the Ryznar stability index (RI) [24], the Puckorius scaling index (PSI) [25], and the calcium carbonate precipitation potential (CCPP) [26] index [27,28], are based on calcium carbonate precipitation measures. The corrosion indices used in this study are summarized in Table 1.

In this study, a windows-based computer program (Water Corrosion Index Calculator), previously developed by the corresponding author, was used for the calculation of corrosion indices [30]. The ionic strength was calculated using Lewis–Randall equation and the electroneutrality of water was checked by evaluating the percent difference of the sum of cations and anions. This software is available upon request from the corresponding author. All statistical analysis in this study was performed using R programming language [31]. ArcView GIS Ver.9.3 software was used for mapping and spatial analysis [32].

## 3. Results and discussion

Summary statistics of the measured water quality in distribution system are shown in Table 2. The 95% confidence interval (CI) for pH of the water samples in the distribution system was $7.43 \pm 0.18$. Typically pH below 7 indicates that corrosion is likely to occur in metallic and cementitious materials [33].

The 95% CI for TDS of the water samples was $290.79 \pm 79.96$ mg/L. TDS is an aggregate parameter that is defined as the sum of all non-volatile dissolved salts in the water sample. It is usually correlated with concentration of ions or conductivity of the water [33]. The dissolved solids also influence the formation of protective films, but the impact depends on the nature of the dissolved solids. For instance, if sulfates and chlorides are the major anionic contributors to TDS, corrosivity toward iron is increased. However, if bicarbonate is the major contributor, corrosivity is decreased [33]. Sulfates and chlorides cause pitting corrosion of metallic pipe by diffusing through the protective metallic oxide films and causing intense localized corrosion. Chloride, due to its smaller size, is about three times as active as sulfate in causing pitting corrosion. The ratio of the chloride plus the sulfate to the bicarbonate $((Cl^- + SO_4^{2-})/HCO_3^-)$ has been used by some corrosion experts to estimate the corrosivity of water [22,34,35].

Fig. 1 shows the correlations between TDS and $HCO_3^-$, $SO_4^{2-}$ and $Cl^-$ observed in this study. From Fig. 1 it can be observed that $HCO_3^-$ ion with a high coefficient of determination ($R^2 = 0.98$) was a major contributor to TDS, while $Cl^-$ and $SO_4^{2-}$ contribute less to TDS in comparison with $HCO_3^-$. In addition, the values of standardized (beta) coefficient were also used to identify the variable that had a greater effect on the TDS, even when the variables are measured in

Table 1
Main characteristic of water corrosion indices

| Index | Formula | Calculation | Type | Threshold | Ref. |
|---|---|---|---|---|---|
| Langelier saturation index (LSI) | LI = pH − $pH_s$ | $pH = -\log[H^+]$<br>$pH_s = pK_{a2} + pCa^{2+} - pK_s - \log(2[Alk_{initial}]) - \log\ \gamma_m$ | Qualitative | <0 | [23] |
| Ryznar stability index (RSI) | RI = $2pH_s$ − pH | $[Alk_{initial}] = \left[CO_3^{2-}\right] + 1/2\left[HCO_3^-\right] + 1/2[OH^-] - 1/2[H^+]$ | Qualitative | >7 | [24] |
| Puckorius scaling index (PSI) | PSI = $2pH_s$ − $pH_{eq}$ | $C_T = \frac{[HCO_3^-]([H^+]^2 + K_{a1}[H^+] + K_{a1}K_{a2})}{K_{a1}[H^+]}$<br>$pH_{eq} = -\log\{H^+\}$<br>$\alpha_1 = \frac{K_{a1}\left\{H^+\right\}}{\left\{H^+\right\}^2 + K_{a1}\left\{H^+\right\} + K_{a1}K_{a2}}$<br>$\alpha_2 = \frac{K_{a1}K_{a2}}{\left\{H^+\right\}^2 + K_{a1}\left\{H^+\right\} + K_{a1}K_{a2}}$<br>$X \approx \frac{C_T\left(\left\{H^+\right\} + 2\alpha_2\right) + \frac{K_W}{\{H^+\}} - \left\{H^+\right\} - Alk_{initial}}{(\alpha_1 + 2\alpha_2 - 2)}$ | Qualitative | >7 | [25] |
| Calcium carbonate precipitation potential (CCPP) | CCPP = $X$ × 100,086.9 | $K_S = \left(\left[Ca^{2+}\right] - X\right)(C_T - X)\alpha_2$<br>A trial-and-error method can be used to find the value of $X$ | Quantitative | <−10 | [26,29] |

Notes: $[Alk_{initial}]$ = initial alkalinity(mole/L), $Alk_{initial}$ = initial Alkalinity (eq/L), $\alpha_1$ and $\alpha_2$ = ionization factor for carbonate system, $\{H^+\}$ = proton activity at equilibrium(mole/L), $K_{a1}$ = corrected equilibrium constant for carbonic acid and bicarbonate, $K_{a2}$ = corrected equilibrium constant for bicarbonate and carbonate, $K_W$ = corrected equilibrium constant for water, $K_s$ = solubility product of $CaCO_3$ = $\{Ca^{2+}\}\{CO_3^{2-}\}$, $X$ = amount of $CaCO_3$ that will precipitate (or dissolve) at an equilibrium(mole $CaCO_3$/L), $C_T$ = total carbonate species (mole/L), pH = actual (measured) pH, $pH_s$ = pH at saturation point, $pH_{eq}$ = pH at equilibrium point, $\gamma_m$ = activity coefficient for monovalent ions.

Table 2
Descriptive statistics of water characteristics in distribution system

| Parameter | Unit | N[a] | Mean | SD[b] | Min. | Max. | CI 95%[c] | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Upper | Lower |
| pH | – | 24 | 7.43 | 0.46 | 6.45 | 8.62 | 7.61 | 7.24 |
| $T$ | ℃ | 24 | 19.36 | 5.29 | 10.40 | 27.30 | 21.48 | 17.25 |
| $SO_4^{2-}$ | mg/L | 24 | 36.05 | 29.55 | 0.70 | 82.00 | 47.88 | 24.23 |
| $Fe^{2+}$ | mg/L | 24 | 0.05 | 0.05 | 0.01 | 0.16 | 0.07 | 0.03 |
| $Ca^{2+}$ | mg/L | 24 | 52.74 | 34.55 | 7.20 | 105.10 | 66.56 | 38.91 |
| ALK | mg $CaCO_3$/L | 24 | 141.00 | 88.41 | 19.20 | 252.00 | 176.37 | 105.63 |
| $Cl^-$ | mg/L | 24 | 23.83 | 19.51 | 1.40 | 50.80 | 31.63 | 16.03 |
| TDS | mg/L | 24 | 290.79 | 199.87 | 38.40 | 570.90 | 370.75 | 210.83 |
| $SO_4^{2-}/HCO_3^-$ | – | 24 | 0.11 | 0.06 | 0.01 | 0.28 | 0.13 | 0.08 |
| $SO_4^{2-}+Cl^-/HCO_3^-$ | – | 24 | 0.33 | 0.11 | 0.11 | 0.50 | 0.38 | 0.29 |
| LI | – | 24 | −0.60 | 0.74 | −2.79 | 0.40 | −0.31 | −0.90 |
| RI | – | 24 | 8.63 | 1.43 | 6.91 | 12.03 | 9.20 | 8.06 |
| PSI | – | 24 | 8.18 | 0.85 | 7.22 | 10.12 | 8.52 | 7.83 |
| CCPP | mg $CaCO_3$/L | 24 | −10.95 | 17.38 | −42.90 | 19.76 | −4.00 | −17.91 |

[a] Number of observations.
[b] Standard deviation.
[c] Confidence interval 95% for the mean.

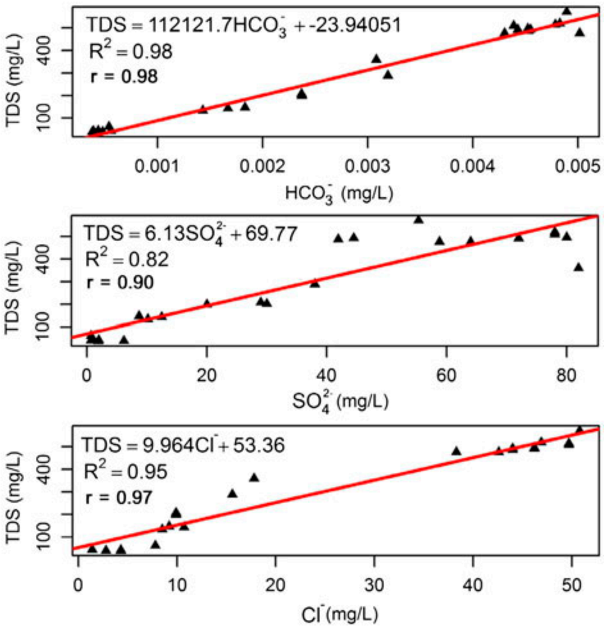

Fig. 1. Correlations between TDS and $HCO_3^-$, $SO_4^{2-}$ and $Cl^-$.

different units of measurement. The values of standardized coefficient for $HCO_3^-$, $SO_4^{2-}$, and $Cl^-$ were calculated to be 0.54, 0.12, and 0.34, respectively. $HCO_3^-$ has a higher standardized coefficient and therefore is a larger component of the TDS relative to sulfates and chlorides. The molar ratio of $SO_4^{2-}/HCO_3^-$ is a predictive ratio to the type of the scale, if it is either $SO_4^{2-}$ or $CO_3^{2-}$ scale [6]. A value less than 1 indicates high $CO_3^{2-}$ scale (i.e. >80%) and low $SO_4^{2-}$ scale while a value between 1 to 10 indicates medium to high $CO_3^{2-}$ scale and medium $SO_4^{2-}$ scale. The $SO_4^{2-}/HCO_3^-$ ratio calculated from the water sampling data was $0.11 \pm 0.025$. This criterion, proposed by Singley [33], indicates that Hamedan's water is mildly corrosive.

The CCPP is a mechanistic model that estimates the theoretical amount of calcium carbonate that will be precipitated through equilibration of a given water [26,36]. Some practitioners view the CCPP as an unambiguous parameter that can be used in the context of guidelines or regulations without invoking misunderstanding [26,29]. This index is negative for undersaturated waters, zero for saturated waters, and positive for oversaturated waters [37–39], and quantifies the mass of $CaCO_3$ precipitated [26,40]. The inhibition of incrustation and corrosion is ideally characterized by the following conditions [37]:

(1) water should be supersaturated by 4–10 mg/L with calcium carbonate;
(2) calcium and alkalinity values, expressed as calcium carbonate, should each be greater than 40 mg/L;
(3) alkalinity: (chloride plus sulfate) ratio should be at least 5:1;
(4) pH should be in the range of 6.8–7.3.

In many studies, CCPP is used as standard index for the $CaCO_3$ precipitation [26,41,42]. For example, in the USA, a range for CCPP values of between 4 and 10 mg/L as $CaCO_3$ is the most common recommendation [38]. A similar recommendation appears in the most recent WHO guidelines [43]. Elsewhere, and especially in South Africa where soft waters abound, lower CCPP ranges of between 2 and 5 mg/L as $CaCO_3$ [44], and even between 1 and 2 mg/L as $CaCO_3$ are applied [45]. The CCPP index predicts tendency to precipitate or to dissolve $CaCO_3$ in addition to its quantity as well. The CCPP can be calculated with computerized water chemistry models [46]. However, in field practice, CCPP is not widely used because of its computational complexity.

The correlation between each dimensionless empirical index (LI, PSI, and RI) and the mechanistic CCPP index was computed to determine the threshold value of the index. The threshold point for each index was defined as the point where the CCPP was zero.

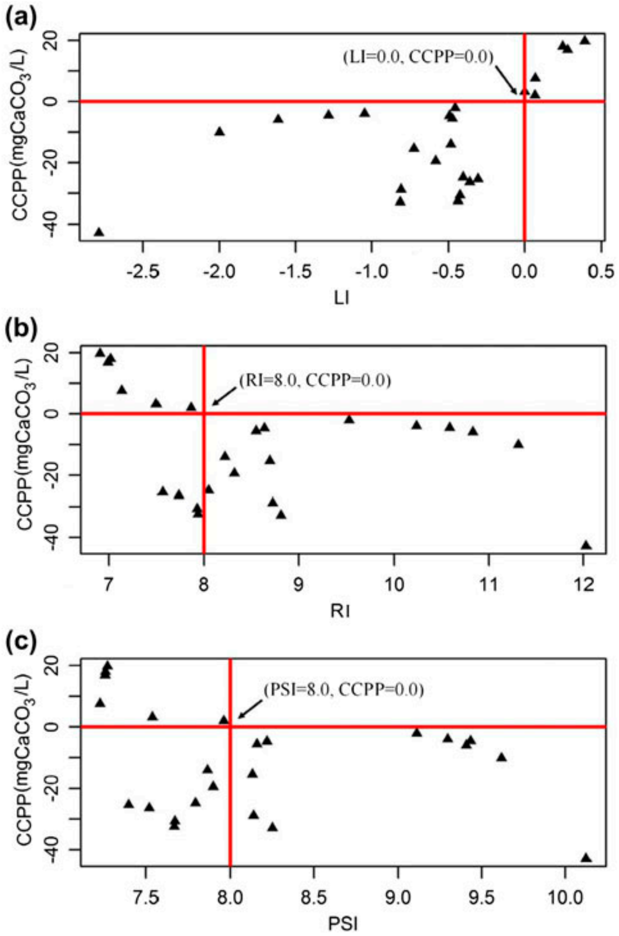

Fig. 2. Critical values for LI (a), RI (b) and PSI (c) indices.

By definition, the LI is zero when the CCPP is also zero as it is the difference between pH of water and the theoretical $pH_s$ at which calcium carbonate precipitates. Water that has a negative LI ($pH < pH_s$) is undersaturated with respect to calcium carbonate and potentially corrosive. Conversely, waters with positive LI ($pH > pH_s$), are supersaturated with $CaCO_3$ and form protective scales on pipe surfaces. A slightly positive LI ($pH = pH_s + 0.3$) is recommended as an operational water treatment goal to mitigate iron release in distribution systems [47].

The threshold values (Fig. 2) of PSI and RI indices were determined to be 8. The Ryznar index (RI) is obtained by changing the placement of the pH and $pH_s$ to yield only positive values. Water having an RI of 6.0 or less is definitely scale forming, while an index above 7.0 may not give a protective coating of calcium carbonate. Corrosion would become an increasingly greater problem as the RI increases above 7.5 or 8.0 [24].

In addition to the LI and RI, the PSI [25] index was also analyzed. The LI and RI indices do not account for the buffering capacity of water and the maximum quantity of precipitate that can form in bringing water to equilibrium. The PSI incorporates an estimate of buffering capacity of the water into the index. The PSI formula is valid only for pH values below 8.3 (the phenolphthalein reversion point). So the use of PSI in pH values over 8.3 is best avoided [48].

It should be noted that the corrosion indicators are applicable for steady-state conditions. Non-steady-state conditions, i.e. when water is in a transition condition from mild to severe corrosion or from scaling to neutral or vice versa, are complex and not easily determined [49]. Pilot studies by Taylor et al.

Table 3
Statistical analyses of the mean of corrosion parameters

| Parameter | Mean | *t* | N.H. | A.H. | *P*. value |
|---|---|---|---|---|---|
| CCPP | −10.95 | −0.26 | <=−10 | >−10 | 0.604 |
| | | −1.67 | <=−5 | >−5 | 0.946 |
| | | −1.67 | =−5 | <>−5 | 0.106 |
| RI | 8.63 | 2.14 | >=8 | <8 | 0.978 |
| | | 2.14 | =8 | <>8 | 0.042 |
| | | −1.27 | <=9 | >9 | 0.893 |
| | | −1.27 | =9 | <>9 | 0.213 |
| PSI | 8.18 | 1.00 | >=8 | <8 | 0.836 |
| | | 1.00 | =8 | <>8 | 0.326 |
| LI | −0.60 | −3.98 | <=0 | >0 | 0.999 |
| | | −3.98 | =0 | <>0 | 0.000 |
| pH | 7.43 | −9.35 | >=8.3 | <8.3 | 0.000 |

Notes: *t*: student-t statistic, N.H.: null hypothesis, A.H.: alternative hypothesis.

[49] have established that the transition period in corrosion response due to change in water quality can be as high as 2–4 weeks. However, even though the indices are not responsive to localized changes in water quality or flow reversals over a shorter duration, they do provide valuable information over longer durations of quasi-steady-state response to changes in water quality. In order to facilitate direct comparison and statistical analysis in this study, we assume that the response to change in water quality is instantaneous. Therefore, the results of this study should be viewed within the scope of limitations imposed due to temporal variations in transition states described by Taylor et al. [49].

The statistical analyses of the corrosion indices are shown in Table 3. It was found that at $\alpha = 0.05$ (95%

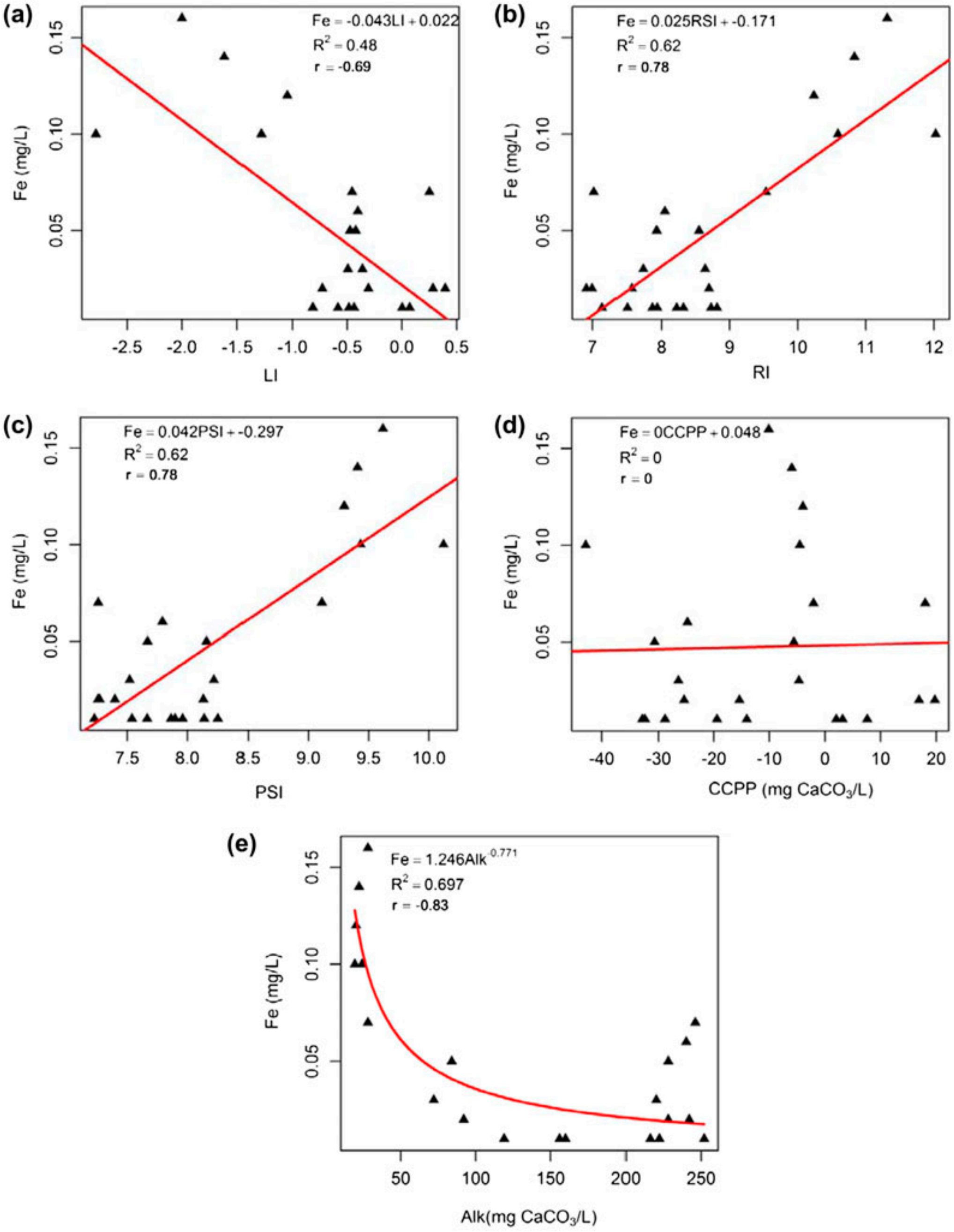

Fig. 3. Scatter plots of corrosion indices (a)–(d) and alkalinity (e) on iron concentration.

Confidence level) the population mean for LI index is significantly less than the hypothesized test mean of zero (Table 3). This shows that the water has a negative LI value ($pH < pH_s$), and is undersaturated with respect to calcium carbonate. In general, a corrosion free system exists when the LI is greater than −0.5 for cold water and 0.0 for hot water [50]. Thus, Hamedan's water system is slightly corrosive and non-scale forming with respect to the calcium carbonate. This is also evident from the inverse relationship (correlation coefficient ($r$) = −0.69) between LI and iron concentration observed in Fig. 3(a).

The positive correlation ($r = 0.78$) of RI with iron Fig. 3(b), further illustrates that pH has a significant influence on the release of iron in the distribution system. The RI is empirical and applies only to systems where the environment at the pipe wall is quite different from that of the bulk water. This is in contrast with the LI index, which is most useful in predicting events in bulk systems such as reservoirs. The use of both indices provides insights into events occurring during distribution and storage [51]. Thus in this study, the values of LI and RI suggest that pH is a key factor responsible for the aggressiveness of the water.

While some studies have indicated that no correlation exists between these indices and corrosive tendency of water [52], other studies have shown that the LI and RI are significant indicators of corrosion in unlined metal pipes and cementitious materials [53]. The difference between the conflicting conclusions from different studies can be deduced from the time dependent response of the metallic surfaces to changing water quality as described by Taylor et al. [49].

Statistical analysis was used to assess the iron release potential with regard to RI index. The null hypotheses were used (Table 3) to determine if the population mean for this index was greater than or equal to the threshold value of 8. It was determined that the population mean for the RI index is significantly ($\alpha = 0.05$) equal to 9. Based on the interpretations for this index [54], the water may have a tendency to dissolve scale and likely release iron.

The population mean for the PSI index was equal to the threshold value of 8 ($\alpha = 0.05$). The interpretation for this index is similar to RI index. Thus, the water may have a tendency to dissolve scale and corrosion likely to occur. Statistical analysis for assessing the value of pH showed that the population mean of pH is significantly ($\alpha = 0.05$) less than the test mean (8.3). Thus, the PSI index can also be used to assess corrosion potential in this water system. As with the RI index, a positive correlation between PSI index and iron concentration ($r = 0.78$) can be seen in Fig. 3(c). This result shows the PSI index can be monitored as a measure of iron release in water distribution system. Table 4 presents the common interpretation of the CCPP.

The mean value of CCPP index for all water samples was determined to be −10.95 ± 6.96 mg $CaCO_3$/L. However, the *t*-test was used to determine that the population mean for the CCPP index was not significantly ($\alpha = 0.05$) different from −5. Therefore, the CCPP also indicates that the water has a tendency to be mildly corrosive (Table 4).

Many studies showed that lower iron concentrations in distribution systems have been associated with higher alkalinities [55,56]. The correlation coefficient ($r = -0.83$) of alkalinity on the concentration of iron (Fig. 3(e)) indicated that iron release in distribution system is negatively associated with alkalinity. Similar exponential relationship was observed by Imran et al. [16]. They conclude that alkalinity addition can be a simple and viable alternative reducing red water phenomenon in iron drinking water pipes that receive different source waters.

The measured values of calcium and alkalinity were determined to be 52.74 ± 13.82 and 141.0 ± 35.37 mg/L as $CaCO_3$, respectively. The alkalinity/(chloride + sulfate) ratio is 3.31 ± 0.74 which is lower than 5. This means the sum of $Cl^-$ and $SO_4^{2-}$ ions are considerable and may contribute to corrosion. Water Research Centre [57] suggests that water can be regarded as potentially corrosive when ($Cl^- + SO_4^{2-}$) > 50 mg/L. The mean value of $Cl^- + SO_4^{2-}$ for the water samples was 59.88 ± 47.18. This indicates that the distribution system could experience a range between 13 to 107 mg/L of $Cl^- + SO_4^{2-}$. Higher values lead to increased EC, facilitates the flow of corrosion current, and simultaneously, hinders the creation of protective layers [58]. Thus, to reduce the effects of sulfate and chloride anions on the corrosion potential of the water, the blending of the waters from different sources should be done in such a way that the sum of these two anions is kept below 50 mg/L. Where this is not possible, the potential release can be mitigated by an increase in alkalinity.

Table 4
Interpretation of the CCPP

| Description | CCPP value as mg$CaCO_3$/L |
|---|---|
| Scaling (protective) | >0 |
| Passive | −5 to 0 |
| Mildly corrosive | −10 to −5 |
| Corrosive (aggressive) | <−10 |

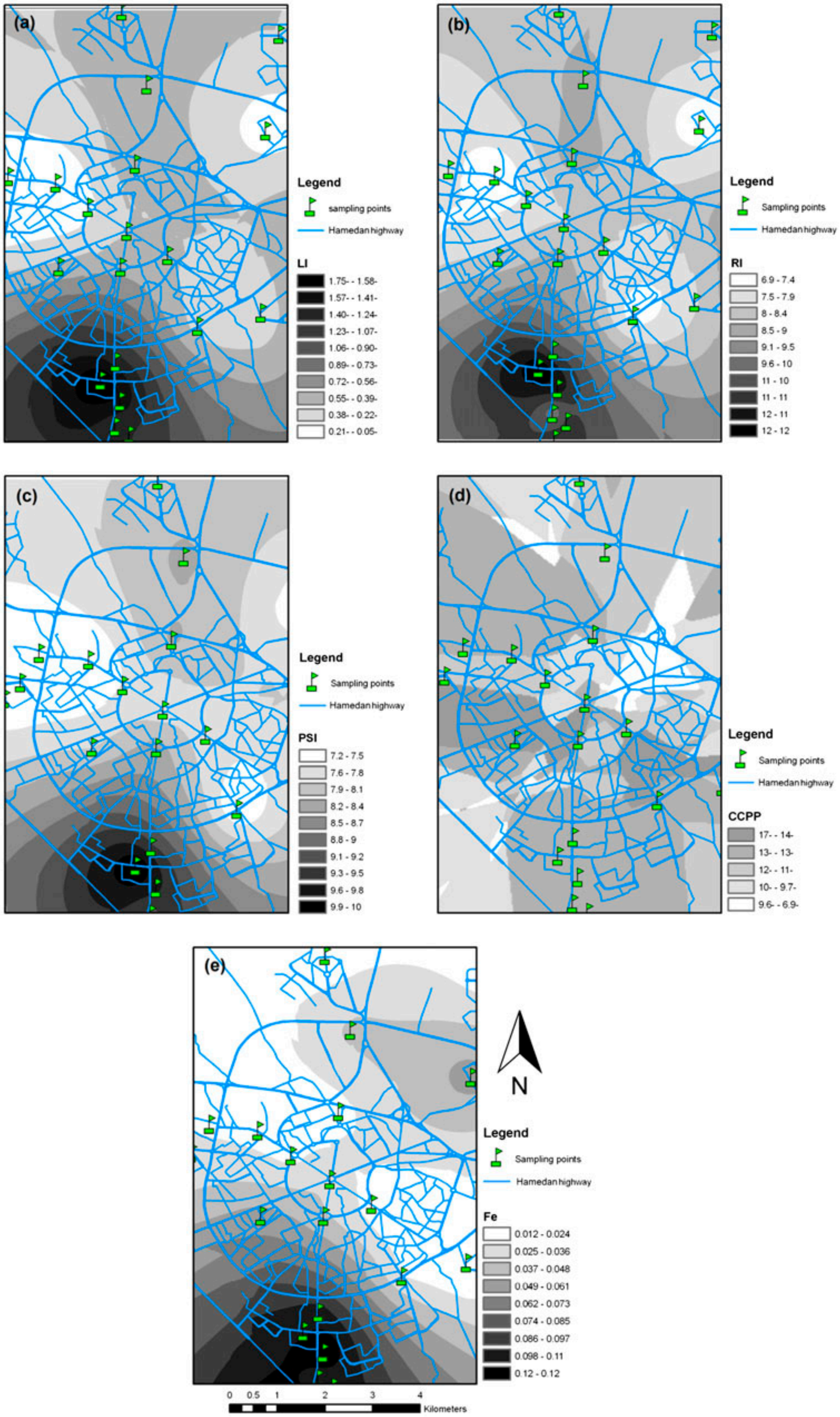

Fig. 4. The prediction maps of corrosion indices (a)–(d) and iron concentration (e) based on the Kriging interpolation model.

As previously mentioned, about only 15% of pipes used in the distribution system are iron pipes (10% DIP and 5% GCI). The GCI pipes were gradually superseded by DIP pipes and there is currently no new manufacture of GCI. In DIP pipes although an internal cement mortar lining usually serves to inhibit corrosion from the fluid being distributed, however, like most ferrous materials, it is susceptible to corrosion [59]. Despite the mildly corrosive nature of the distributed water in Hamedan, the iron level at the consumer's tap is relatively low. This is hypothesized to be due to the low proportion of iron pipes in the distribution system.

Iron release to the drinking water in different zones of the distribution system is dependent on two factors: (1) the proportion of iron pipes in that zone and (2) the chemistry of the distributed water that occurs due to blending of different sources at that location. Data about the spatial location of the iron pipes within the system was not available. Therefore, the relative proportion of iron pipes in different zones is unknown. However, these can be estimated by visualizing the spatial extent and variation of iron concentration in distribution system with layers of corrosion indices constructed from the sampling point data. Ordinary Kriging method of interpolation derived from regionalized variable theory was used for this purpose. The methodology involves expressing spatial variation of the property in terms of a variogram, and thereby minimizing the prediction errors which are themselves estimated [60]. The output raster map of the Kriging interpolation containing the estimates of different indices at different locations was arranged in several bins. Several bins with equal ranges were used to slice the corrosion indices range from bright color (non-corrosive) to high black (the maximum level for corrosion according to each index).

A spatial data analysis was performed with ArcView GIS to examine the relationship between iron release in distribution system and the LI, RI, and PSI indices. These results are consistent with the results of the previous correlation analysis (Fig. 3). The prediction maps of the corrosion indices and the concentration of iron in the distribution system are shown in Fig. 4(a)–(d) and Fig. 4(e), respectively. The prediction maps of all indices show the water in the south area of the distribution system tends to be corrosive. The water in this zone is predominantly supplied from Morad-beik valley reservoir that is fed by spring waters with low pH (7.3 ± 0.6) and low alkalinity (23.3 ± 3.6). As shown in the Fig. 4(e) the iron concentration in the southern zone of the network is also higher than that in other zones of the network. Relatively high concentration of iron in the southern zone (0.11 ± 0.02 mg/L) in comparison with other zones was consistent with the maps of corrosion indices which show a tendency toward the corrosive conditions in this zone. Although the iron concentration in southern zone of the network is higher than other zones, it is still lower than USEPA's secondary drinking water guidelines (0.3 mg/L) [61]. This could be due to the lower proportion of iron pipes within this zone.

As seen from Figs. 3 and 4, the three qualitative indices namely LI, RI, and PSI were correlated with the amount of iron in the distribution system. Thus, they may be good measures of the pipe corrosion which is resulted from the chemical water characteristics in iron pipes. Though the CCPP is a mechanistic index for calcium carbonate deposition, it was not well correlated with iron release. This indicates that the protective mechanisms for iron pipes in the distribution systems in Hamedan are probably more influenced by pH and alkalinity than by calcium carbonate scale deposition.

## 4. Conclusion

The stability of water in the distribution system with respect to calcium carbonate saturation was evaluated by calculating the three qualitative and one quantitative water corrosion indices. The mean ranges of the LI, RI, PSI, and CCPP indices were −0.60 ± 0.30, 8.63 ± 0.57, 8.18 ± 0.34, and −10.95 ± 6.9, respectively. Based on these values, it can be concluded that the distributed water in Hamedan's water supply system is undersaturated with calcium carbonate and moderately corrosive for iron pipes.

It was observed the iron release in Hamedan's distribution system was negatively correlated with alkalinity and pH. Thus, increasing alkalinity and/or pH can be used as a control measure to reduce iron release. In this case, we recommend that the water be amended with soda ash ($Na_2CO_3$) or sodium bicarbonate ($NaHCO_3$) not only for adjusting the pH but also to increase the alkalinity. As demonstrated in this paper, LI, RI, and PSI indices can be effectively used to monitor the water distribution system for potential release of iron from iron pipes. In this study, the spatial correlation between iron concentration and corrosion indices show that spatial interpolation can be as a useful tool to find the regions within the distribution network parts that have a high potential for the iron release. Furthermore, it was observed that water in the southern zones of Hamedan's water distribution system is not stable. We recommend chemical amendment of the water from Morad-beik springs to reduce the potential for corrosion and iron release in the system. Monitoring for iron in the distributed water indicated that the mean iron release in Hamedan's distribution system was well within the USEPA guideline for iron levels in water. While this is an encouraging finding, we still recommend that mitigation measures for iron pipe corrosion be adopted to reduce further deterioration and degradation of the pipes.

Since the major proportion of pipes used in the Hamedan's water distribution is AC pipes, the release of asbestos in the system is an issue of concern due to the tendency of low hardness, alkalinity, and pH of some water blends. We recommend a similar study to evaluate the potential for asbestos deterioration due to water quality for the distribution system of Hamedan.

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