

Modified Larsons Ratio Incorporating Temperature, Water Age, and Electroneutrality Effects on Red Water Release

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Abstract: Corrosion indices have a historical as well as practical relevance in drinking water treatment. The development of reliable indicators of corrosion related problems, like red water, is an ongoing process in the drinking water industry. Due to the complexity of interaction among the physical, chemical, and biological reactions taking place within a typical distribution system, mechanistic models are difficult to formulate. Even if such a model was available, fitting it to actual field conditions would still be an empirical process. Corrosion indices give simplistic generalizations to complex corrosion phenomena. A modified form of the Larson Ratio that includes the effects of temperature and hydraulic retention time is proposed based on apparent color release data available from a 2 year pilot distribution system study.

DOI: 10.1061/(ASCE)0733-9372(2005)131:11(1514)

CE Database subject headings: Corrosion; Water distribution; Potable water; Water treatment; Water temperature; Water quality; Color; Cast iron.

Background

The recent trend in source water diversification and demand dynamics may result in distribution systems receiving variable water quality over short periods of time. Security measures have placed an emphasis on providing interconnects between isolated distribution systems so that demand can be met in case of emergencies. Utilities have to face the fact that the water quality changes in the source water may no longer have gradual seasonal changes that can be historically predicted. The need is even greater for simple corrosion indices that can evaluate the corrosion potential of the source waters and blends. This will help utilities to develop quick responses to source water changes and timely implementation of corrosion prevention measures.

Temperature and water age have not been given the appropriate significance in evaluation of the indices. Most of the distribution systems are underground and large variation in temperatures are not noticed (McNeill and Edwards 2002). However, significant seasonal variations may exist according to the observations of Volk et al. (2000) who have reported that the corrosion rate in distribution systems is strongly related to seasons and temperature. Temperature changes can cause shifts in the chemical and physical properties of the water, the corrosion scales present on the metal and the nature of the metal itself (McNeill and Edwards 2002; Montgomery 1985).

Corrosion Indices

The Langelier Index (LI) is an indicator of whether suitable conditions exist for the precipitation of calcium carbonate. However, it is commonly used to indicate the stability of the source waters due to a preponderance of evidence that calcium carbonate films inhibit corrosion to some degree (Keysar et al. 1997).

Based on a study in which the authors found that the waters with a positive LI were at least as corrosive as those with a negative LI, Pisigan and Singley (1985) recommend that LI should be used with caution.

A simplified form of these equations has traditionally been used

$$LI = pH - pK_2 + pK_{s0} + \log[Ca^{2+}] + \log[Alk] \quad (1)$$

where K_{s0} =solubility constant for $CaCO_3$ and K_2 =acidity constant for dissociation of bicarbonate.

A positive LI indicates that the water is saturated with $CaCO_3$ and a negative LI indicates that the water is unsaturated with $CaCO_3$. Unsaturated waters tend to remove the protective $CaCO_{3(s)}$ scale and expose the metal surface of the pipes to further corrosion. The general practice is to increase pH by 0.2–1 units above pH_s to prevent corrosion in distribution systems.

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Note. Discussion open until April 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 20, 2004; approved on December 20, 2004. This paper is part of the *Journal of Environmental Engineering*, Vol. 131, No. 11, November 1, 2005. ©ASCE, ISSN 0733-9372/2005/11-1514-1520/\$25.00.

The calcium carbonate precipitation potential (CCPP) is the amount of calcium carbonate that will precipitate or dissolve from the solution as it comes to equilibrium with solid CaCO_3 . This parameter was first proposed by Merrill and Sanks (1978) and is calculated as (Montgomery 1985)

$$\text{CCPP} = (-b + \sqrt{b^2 - 4ac}) / (2a) \quad (2)$$

where, $a=2$; $b=-2[\text{Ca}^{2+}] - \text{Alk}$; $c = \text{Alk}[\text{Ca}^{2+}] - 0.5(K'_{\text{so}}) - [\text{Ca}^{2+}]$. The CCPP is a measure of the actual amount of calcium carbonate that would precipitate in the distribution systems. Riddick developed a corrosion index (RCI) that gives weight to several factors that contribute to corrosion in distribution systems. Source waters are interpreted as extremely noncorrosive in the range of 0–5, noncorrosive in the range of 6–25, moderately corrosive in the range of 26–50, corrosive in the range of 51–75, very corrosive in the range of 76–100 and extremely corrosive above 100

$$\text{RCI} = \frac{75}{\text{Alk}} \left[\text{CO}_2 + \frac{1}{2}(\text{hardness} - \text{Alk}) + \text{Cl}^- + 2\text{N} \right] \left(\frac{10}{\text{SiO}_2} \right) \times \left(\frac{\text{DO} + 2}{\text{Sat. DO}} \right) \quad (3)$$

where CO_2 is expressed in milligrams per liter, hardness and alkalinity in milligrams per liter CaCO_3 , chloride ion in milligrams per liter, nitrate ion in milligrams per liter, dissolved oxygen in milligrams per liter and oxygen saturation in milligrams per liter (Singley 1981; USEPA 1984).

In 1944 Ryznar used the pHs as calculated by Langelier equation to produce a stability index (RSI). This index yields only positive values: the larger the value the more corrosive the water. A value of 6.5–7.0 indicates saturated water. This value is based on the observations made by Ryznar (1944) on the formation of $\text{CaCO}_{3(s)}$ on a glass tubing. At values exceeding 7 no $\text{CaCO}_{3(s)}$ was deposited

$$\text{RSI} = 2\text{pH}_s - \text{pH}_o \quad (4)$$

Ryznar generated a curve based on actual field results showing the encrustation or corrosion of steel mains as a function of RSI (Singley 1981; US EPA 1984).

A rearranged form of the solubility expression was used by McCauley in 1960 and termed as the driving force index (DFI). McCauley stated that the driving force index is the exact amount of the tendency to deposit calcium carbonate, being a statement of the law of mass action which defines all chemical precipitations (Dye 1964)

$$\text{DFI} = (\text{Ca}^{2+} \cdot \text{CO}_3^{2-}) / (K_{\text{so}} \cdot 10^{10}) \quad (5)$$

The concentrations are expressed in milligrams per liter as CaCO_3 . A DFI of 1 denotes water saturated with respect to $\text{CaCO}_{3(s)}$. A DFI exceeding 1 indicated over saturated water and a DFI less than 1 indicates under saturated water. This relationship was useful in predicting the amount of precipitate that would be formed (Singley 1981; US EPA 1984).

The aggressiveness index (AI) is a measure of the tendency of water to deteriorate the structure of asbestos cement pipes. It is defined as

$$\text{AI} = \text{pH} + \log(\text{AH}) \quad (6)$$

where A =alkalinity and H =hardness, both expressed in milligrams per liter as CaCO_3 . Waters with AI equal to or exceeding 12 are considered nonaggressive; those with values <10 are

highly aggressive and those between 10 and 12 are moderately aggressive.

The Larson ratio (LR) is developed from the relative corrosive behavior of chlorides and sulfates to the protective properties of bicarbonate. The writers deduced that the corrosivity of air-saturated waters is dependent on the proportion of corrosive agents to the inhibitive agents and their concentrations (Larson and Skold 1958). Larson and Skold (1957) observed that calcium in the presence of alkalinity, regardless of pH or saturation index, is an effective inhibitor of corrosion

$$\text{LR} = ([\text{Cl}^-] + [\text{SO}_4^{2-}]) / ([\text{HCO}_3^-]) \quad (7)$$

where [] is expressed in milliequivalents per liter.

Any value above 0.5 is considered corrosive. Feigenbaum et al. (1978) showed poor correlation between the available calcium carbonate based corrosion indices and field results from the hard saline waters of the Negev Desert in Israel. An empirical index was developed that incorporated the effect of calcium carbonate solubility as well as chloride and sulfate ions

$$Y = \text{AH} + B(\text{Cl}^- + \text{SO}_4^{2-}) \exp(-1/\text{AH}) + C \quad (8)$$

where $A=3.5 \times 10^{-4}$; $B=0.34$; $C=19$; and $H = ([\text{Ca}^{2+}] \times [\text{HCO}_3^-]^2) / [\text{CO}_2]$. All concentrations expressed as parts per million, except $[\text{HCO}_3^-]$ which is expressed as milligrams per liter CaCO_3 .

The values obtained for Y indicate that if Y is less than 200 the waters are corrosive, moderately corrosive in the range of 200–500, and not very corrosive for values exceeding 500 (Singley 1981; USEPA 1984).

Based on laboratory loop studies and field investigations, Pisigan and Singley (1987) observed that an increase in buffer capacity at constant alkalinity (100 mg/L as CaCO_3) in the pH range of 6.0–9.0 decreased the corrosion rate of mild steel. However, raising the buffer capacity by raising alkalinity was counterproductive due to a corresponding increase in ionic strength and conductivity. The authors recommend the buffer capacity as a better indicator of corrosion rates than alkalinity. They related corrosion rates to the ratio $\beta/\text{Cond}^{3/2}$, where β =buffer capacity and Cond =conductivity. The authors report that increasing the ratio causes an increase in corrosion.

Rossum and Merrill (1983) conducted a review of some common calcium carbonate based indices. Based on the correlation among the indices the authors conclude that the LI, RSI, and AI bear no clear relationship to CCPP. The authors conclude that though LI and DFI are satisfactory indicators of whether the water is saturated with respect to $\text{CaCO}_{3(s)}$, they should not be used for any other purpose. The authors further observed a redundancy between certain indices like DFI, AI, and LI. They recommend the CCPP as the index best suited to describe $\text{CaCO}_{3(s)}$ saturation state.

Singley (1981) conducted a survey of existing corrosion indices and concluded that all indices developed were based on certain simplifying assumptions that were applicable to the specific cases for which they were developed. Therefore, no single corrosion index is applicable universally. Singley (1981) observed that based on the review of literature and experience; there are a number of water quality parameters that need to be considered in addition to calcium carbonate solubility. The water quality parameters listed by Singley (1981) were calcium, magnesium, alkalinity, carbonate, carbon dioxide, pH, chlorides, sulfates, ionic strength, conductivity, total dissolved solids, color, hydrogen sulfide, buffer capacity, phosphate, silica, dissolved

oxygen, chlorine, and temperature. Singley (1981) advises that the most useful form of corrosion index would consider all relevant factors for the water, but must be designed in such a way that the protective mechanisms for a given water would predominate in the calculation of the index.

Traditional calcium carbonate solubility based indices have a tenuous relationship to actual corrosion rates in the distribution systems. This however does not discount their importance in source water treatment and stabilization. Though small deviations from the pH of calcium carbonate stability will not affect corrosion rates in old pipes to a significant extent, a large sustained change in the pH would have a definite impact on the corrosion resistance of old pipes.

The present study involved collection of pilot scale data using blends of varying source waters to assess the iron corrosion potential of cast iron and galvanized pipe materials. The resulting data was evaluated to determine the accuracy of the preceding historical corrosive indexes and propose a modification to the Larson index.

Materials and Methods

Pilot Distribution System Design

The pilot distribution system (PDS) is composed of 18 different distribution lines. Lines 1–14 are hybrid lines that have four different materials: PVC, unlined iron, lined iron, and galvanized iron pipes. The average length of each hybrid PDS is 27.7 m (91 ft) and is composed of 5.8 m (19 ft) of PVC, 5.8 m (19 ft) of lined iron, 4 m (13 ft) of unlined iron, and 12.2 m (40 ft) of galvanized iron pipes in that order. The diameter of the PVC, lined iron and unlined iron pipes is 0.15 m (6 in.) and the diameter of the galvanized iron pipe is 0.05 m 2 in. Line 15 is composed entirely of unlined iron pipe. Similarly lines 16, 17, and 18 are composed of lined iron, PVC, and galvanized iron pipes, respectively. The PDS was constructed of aged pipes that were obtained from existing utility distribution systems. The pipes were removed from the member government's distribution networks, wetted, capped, and transported to the pilot site. Once onsite, the pipes were assembled and allowed to equilibrate with groundwater over a period of 5 months (Cullen 2002). After equilibrium was established, different blends were introduced into the PDS. The project was divided into multiple phases; each of 3 months duration. Similar blends were used in alternate phases (Phases I–IV) to evaluate the effect of seasonal conditions on the PDS and related water quality. Phase V experiments were configured to assess the individual impact of anions (chlorides, sulfates, and alkalinity).

Pilot Source Waters

The pilot plant facility was constructed in such a way that different source waters having different chemical characteristics that simulate the proposed changes could easily be produced. The different pilot processes and their mode of production are shown in Table 1. The finished water qualities from these pilot processes were set to match the existing or future sources of water proposed by TBW. All the source waters were chloraminated to achieve a target chloramine of 4 mg/L as Cl₂. All source waters were stabilized to a achieve a slight positive LI of +0.2 pH units by addition of sodium bicarbonate for alkalinity, calcium chloride for calcium hardness and sodium hydroxide for pH adjustment.

Table 1. Mode of Production of Simulated Source Waters

Source waters	Method of production
G1	Aeration of calcium carbonate raw groundwater representing historical groundwater usage.
S1	Ozonation and subsequent treatment with biological activated carbon of Hillsborough river surface water coagulated with ferric sulfate, settled and filtered. This simulates the TBW surface water treatment facility.
RO	Reverse osmosis membrane permeate of calcium carbonate raw groundwater, with addition of ocean salt to simulate desalination. This simulates the TBW reverse osmosis desalination plant.
G2	Lime softening of raw groundwater.
G3	Lime softening of blend of G1, S1, and RO waters.
G4	Nanofiltration of blend of G1, S1, and RO waters.
S2	Nanofiltration of Hillsborough river surface water coagulated with ferric sulfate, settled, and filtered.

Note: All waters were stabilized to positive Langelier Index and chloraminated.

Maintaining a slight positive LI for the source water eliminated the confounding that would have been associated with introducing waters (such as reverse osmosis permeate) that had minimal alkalinity and calcium content. Different blends of the pilot source waters outlined in Table 1 were introduced into the PDS. The range in water quality due to these blends is given in Table 2.

Pilot Distribution System Operation

The pilot distribution system was operated at a 5 day hydraulic retention time (HRT) initially (Phases I–III) to simulate dead end conditions. The HRT was changed to 2 days during Phases IV and V to permit maintenance of chlorine residual. Different source waters and their blends were introduced into the PDS by dosing pumps feeding individual influent standpipes for each PDS. The PDS were flushed once a week during the 5 day HRT period

Table 2. Variation in Water Quality Parameters

Parameter	Analytical method	Minimum	Maximum	Average
Alkalinity (mg/L as CaCO ₃)	SM 2320 B	51	210	106
Calcium (mg/L)	SM 3111 B	23	88	50
Chlorides (mg/L)	SM 4500-Cl-B	19	100	46
Sulfate (mg/L)	SM 4110	4	232	60
Sodium (mg/L)	SM 3500 Na-B	12	65	35
Silica (mg/L)	SM 4500 Si-D	1	16	10
Dissolved oxygen (mg/L)	SM 4500-O G	6.9	12.2	8.3
Total chlorine (mg/L as Cl ₂)	SM 4500-Cl-G	3.0	6.0	4.6
UV-254 (cm ⁻¹)	SM 5910 A	0.0233	0.0688	0.0439
Conductivity (μS)	SM 2510 B	331	707	489
pH	SM 4500-H+B	7.8	8.4	8.1
Temperature (°C)	Direct reading	16.8	27.0	23.5
Hydraulic retention time (days)	—	2	5	

Note: All techniques designated with "SM" referenced in *Standard Methods* (APHA/AWWA/WEF 1995).

Table 3. Blends Used for Different Pilot Distribution Systems (PDS) Over the Period of the Study

PDS	Phases I and III	Phases II and IV
1	100% GW	100% G2
2	100% G2	100% GW
3	100% SW	100% S2
4	100% G4	100% G3
5	100% RO	100% SW
6	55% GW, 45% SW	68% GW, 32% RO
7	68% GW, 32% RO	55% GW, 45% SW
8	23% GW, 45% SW, 32% RO	60% GW, 30% S2, 10% RO
9	60% GW, 30% SW, 10% RO	23% GW, 45% SW, 32% RO
10	50% G2, 50% SW	62% G2, 24% SW, 14% RO
11	61% G2, 24% SW, 14% RO	50% G2, 50% SW
12	100% G3	100% G4
13	100% S2	100% RO
14	23% GW, 45% SW, 32% RO	60% GW, 30% SW, 10% RO

and once every two weeks for the 2 day HRT period. The flush velocity was 0.3 m/s (1 ft/s) for at least three pipe volumes. Sampling was done once a week at the influent and effluent standpipes for a number of water quality parameters.

Results and Discussions

The pilot study was conducted in multiple phases: Each phase having duration of three months. The first four phases (Phases I–IV) consisted of introducing the source waters (Table 1) and their blends (outlined in Table 3) into the PDS and measuring the water quality changes.

It was observed that the PDS response with regard to iron release could be related to the apparent color and turbidity. Fig. 1 shows the relationship of apparent color to total iron. Since apparent color is more convenient to determine in the field, it was decided to use apparent color as a surrogate measurement for total iron. Apparent color release is therefore a measure of total iron

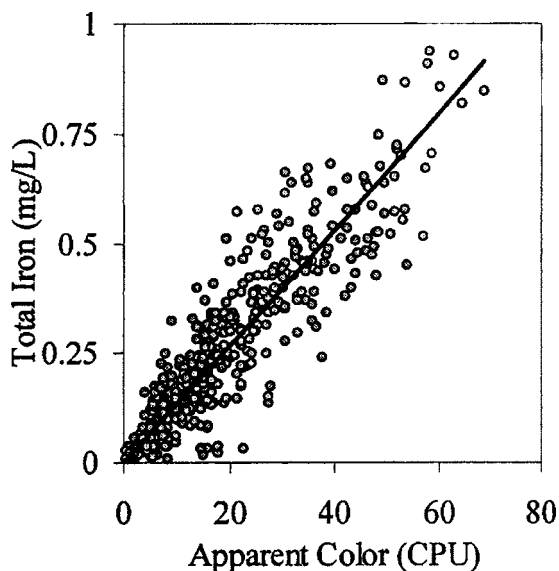


Fig. 1. Apparent color as a substitute for total iron measurement (note: total iron = $0.0132 \times$ apparent color; $R^2 = 0.82$)

Table 4. Variation in Corrosion Indices and Their Correlation with Langelier Index (LI)

Corrosion index	Refs.	Minimum	Maximum	Average	Correlation with LI
LI	i,ii,iii,iv	-0.3	0.98	0.37	1
Calcium carbonate precipitation potential ($\times 10^{-4}$ mol/L)	i,ii,iv	-1	16	7	0.88
Larson ratio	v	0.2	6.3	1.5	-0.6
Aggressiveness index	i,ii	11	13	12	0.99
Ryznar stability index	i,ii	6	9	7	-0.97
Driving force index	i,ii	0	7	2	0.95
Riddick corrosion	i	2	1,080	82	-0.37
Y index	i	26	764	174	0.87

Note: i=Singley (1981); ii=Rossum and Merrill (1983); iii=Merrill et al., (1990); iv=Holm and Schock (1998); v=Larson and Skold (1958).

release from the PDS for the condition of this study. Data were available to evaluate most of the commonly used corrosion indexes in practice. The solution techniques used in this evaluation were obtained from literature (Singley 1981; Rossum and Merrill 1983; Merrill et al. 1990; Holm and Shock 1998; Larson and Skold 1958). Table 4 shows the variation in the different indices obtained using data from Phases I to IV of the study.

It was observed that most of the calcium carbonate indexes were highly correlated. Table 4 gives the correlation coefficients of these indexes with LI. High correlation (>0.8) is noticed between the LI, CCPP, DFI, AI, RSI, and Y index. Therefore, for the purpose of this discussion it is assumed that the LI can be used as a representative calcium carbonate index. This choice is also relevant since the primary and secondary source waters were stabilized using the LI. Fig 2 shows the relationship between LI and the release of apparent color for the averaged water quality from Phases I–IV. A slight trend that indicates higher colors at

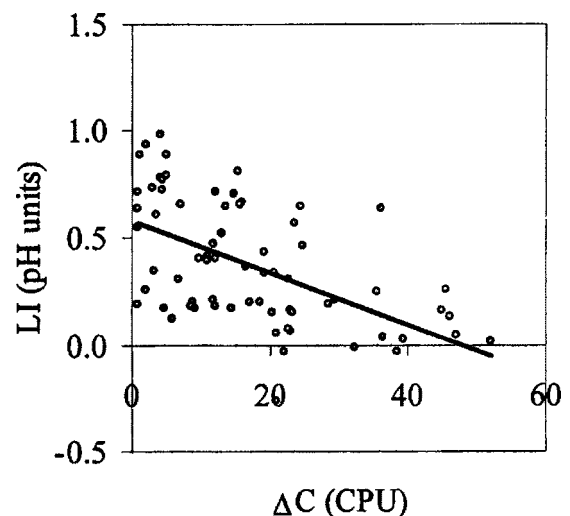


Fig. 2. Variation of Langelier index with increase in apparent color for averaged data from Phases I to IV (note: $R^2 = 0.30$)

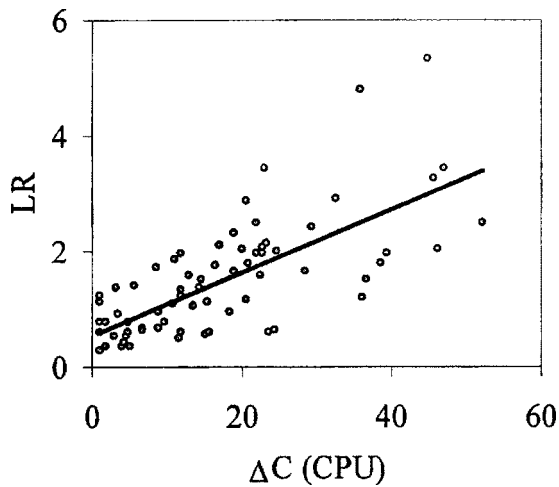


Fig. 3. Variation of LR_1 with increase in apparent color for averaged data from Phases I to IV (note: $R^2=0.50$)

lower LI can be seen. However, as has been observed by many researchers, minor deviations from the LI had little impact on the actual corrosion rates (in this case release of particulate iron from the corrosion scales). Though this graph shows the importance of maintaining slightly positive LI for control of iron release, it does not indicate a strong correlation with the release of apparent color (as can be deduced from the low R^2 for the variance between LI and apparent color). It should be noted here that prediction of corrosion rates based on the calcium carbonate solubility has been cautioned against by a number of researchers (Singley 1981; Rossum and Merrill 1983). LI is used in this case to illustrate a modest role in reducing release of iron.

The Larson ratio was evaluated based on Eq. (7). Fig. 3 shows the relationship between the Larson ratio and the release of apparent color. A better R^2 (compared to the LI) indicates that sulfates and chlorides play an important aggressive role in the release of color from old pipes. A similar relationship based on the conductivity and pH buffer intensity of the waters was proposed by Pisigan and Singley (1987), where the authors indicated that increase in conductivity by alkalinity addition could lead to increased corrosion rates. Similar observations were made by the authors in an earlier work (Pisigan and Singley 1984) that alkalinity is confounded with conductivity. Due to this confounding effect, the model proposed by the authors indicated that increased alkalinity could lead to increased conductivity. Imran (2003) evaluated the significance of different water quality variables on the release of apparent color from the PDS. The empirical relationship based on nonlinear regression analysis was

$$\Delta C = \frac{(Cl^-)^{0.485}(Na^+)^{0.561}(SO_4^{2-})^{0.118}(DO)^{0.967}(T)^{0.813}(HRT)^{0.836}}{10^{1.321}(Alk)^{0.912}} \quad (9)$$

The author observed that the release of color [ΔC (cpu)] was related to temperature [T ($^{\circ}C$)], hydraulic retention time [HRT (days)], initial DO content [DO (mg/L)] and sodium [Na^+ (mg/L)] in addition to alkalinity [Alk (mg/L as $CaCO_3$)], sulfates [SO_4^{2-} (mg/L)], and chlorides [Cl^- (mg/L)]. The inclusion of sodium in the model allows for the separation of the confounding effect between alkalinity and conductivity.

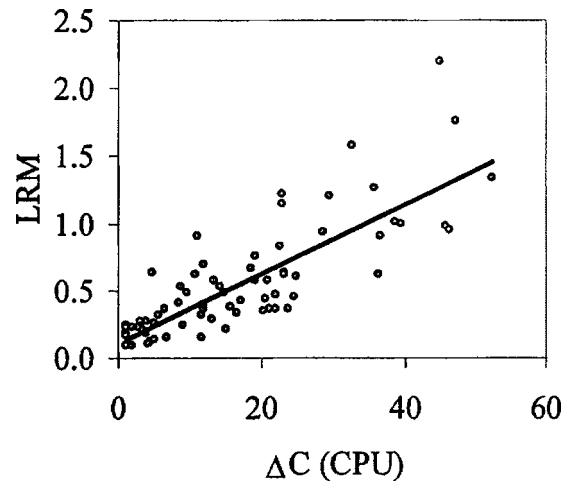


Fig. 4. Variation of modified Larson ratio with apparent color for Phases I–IV averaged data (note: $R^2=0.65$)

Based on the findings of Pisigan and Singley (1987) and Imran (2003), it was possible to propose a modification to the traditional Larson ratio as

$$LRM = \frac{(Cl^- + SO_4^{2-} + Na^+)^{1/2}}{Alk} \left(\frac{T}{25} \right) HRT \quad (10)$$

where LRM=modified Larson ratio. The term $((Cl^- + SO_4^{2-} + Na^+)^{1/2})/Alk$ provides significant improvement over both the Larson ratio and the Pisigan and Singley model.

Potential amelioration measures include alkalinity addition and pH elevation. These measures are typically achieved using sodium compounds ($NaHCO_3$ and $NaOH$). In addition to adding the beneficial species, these compounds also increase the conductivity of the waters. Therefore some of the benefit of adding alkalinity would be offset by the increased conductivity associated with the accompanying cation.

Fig. 4 shows the relationship of the modified Larson ratio on the release of apparent color in the distribution system. A higher R^2 (0.65 versus 0.50) than the Larson ratio indicates that the model is a definite improvement over the original one. The second modification to the original Larson ratio includes the addition of temperature and HRT terms. Though temperature and water age have been recognized as important parameters in the release of corrosion scales and consequent red water problems, there is no comparative index that evaluates the effect of temperature and water age. Water which is noncorrosive at lower temperatures may be classified as corrosive at higher temperatures (McNeill and Edwards 2002; Volk et al. 2000; Montgomery 1985). Though the temperatures in some underground distribution systems may have a small range, significant seasonal variations may exist that may cause changes in corrosive patterns. Since the experimental PDS was laid above ground (in a shed), significant seasonal variations in temperature were observed, that prompted the inclusion of the temperature term. The effect of temperature is also indicated by the empirical model of Imran (2003).

A near linear decrease in apparent color was observed when the HRT was changed from 5 to 2 days in the PDS. Thus corrosive waters may present fewer problems if the HRT is reduced. The model was verified by application to independent data obtained from Phases V and VI of the study (Fig. 5).

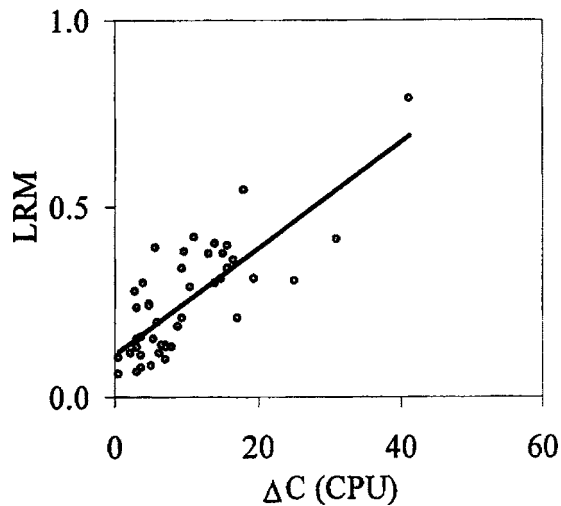


Fig. 5. Modified Larson ratio tested on independent data from Phase V of the study (note: $R^2=0.62$)

The prediction ability for this independent data ($R^2=0.62$) value is similar to that obtained with the original data from Phases I to IV ($R^2=0.65$). The relationships in Eqs. (9) and (10) were developed entirely from data obtained from Phases I to IV, which had source waters different from Phase V. Thus it can be concluded that the modified Larson ratio can be used to evaluate corrosion potential. The writers recommend a value of 0.5 as the cutoff between

corrosive and noncorrosive waters. It was the writers' intention that the cutoff recommended should match that of the original Larson ratio. This was achieved by normalizing the temperature by dividing it by 25 as indicated in Eq. (10). The secondary maximum contaminant limit (SMCL) for color is 15 CPU and the corresponding cutoff value obtained from Fig. 4 is 0.5. From the relationship between apparent color and total iron shown in Fig. 1, 15 CPU would correspond to a total iron of 0.2 mg/L which is less than the SMCL for iron (0.3 mg/L). Therefore, source waters with a value below 0.5 are noncorrosive and those with a value above are corrosive. The term corrosive in this context refers to the tendency of the source waters to cause red water problems.

Conclusions

Based on the evaluation of literature and data from a pilot drinking water distribution system a modification to the traditional Larson ratio is proposed as

$$\text{LRM} = \frac{(\text{Cl}^- + \text{SO}_4^{2-} + \text{Na}^+)^{1/2} \left(\frac{T}{25} \right)}{\text{Alk}} \text{HRT.}$$

It was observed that even noncorrosive waters did release color when higher temperatures and HRT were experienced within the pilot distribution system. Therefore the proposed model incorporates the effect of temperature and HRT.

The model was analyzed on an independent dataset from Phase V of the study. Similar prediction abilities were observed for the original and independent data, confirming the suitability of the modification to the Larson ratio.

Based on electroneutrality constraints an increase in alkalinity by salt addition would lead to a complementary increase in the cations that contribute to increased conductivity and therefore increased potential for color release.

Acknowledgments

The writers specially acknowledge Chris Owen, Tampa Bay Water Authority Quality Assurance Officer, who was the TBW Project Coordinator, and Roy Martinez, AWWA Research Foundation Senior Account Officer, who was the AwwaRF Project Officer, and the following Member Governments: Pinellas County, Hillsborough County, Pasco County, Tampa, St. Petersburg, and New Port Richey. Pick Talley, Robert Powell, Dennis Marshall, and Oz Wisener from Pinellas County, and Dr. Luke Mulford from Hillsborough County are also specifically recognized for their contributions. Several UCF Environmental Engineering students and faculty also contributed significantly to this project and are recognized for their efforts.

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