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PILOT-SCALE VERIFICATION AND ANALYSIS OF IRON RELEASE FLUX MODEL

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Abstract: An original model (Mutoti 2003) was developed mathematically, and empirically, to predict the increase in total iron concentration in distribution systems. This model, referred to as a flux model, relates the increase in iron concentration in a reach of unlined or galvanized iron pipe to the surface area of the pipe in contact with the water. A flux term, defined with a dimension of mass per area per time was used. The effects of water chemistry, pipe material and hydraulic conditions were incorporated into the flux term. This paper describes the verification of the flux model using independent pilot data obtained with variable water quality under worst case, laminar flow conditions. The original model accurately predicted iron release for this independent verification data, with an overall R-squared of 0.80. For laminar flow conditions, the increase in iron concentration is proportional to the flux and the hydraulic residence time, and is inversely proportional to the pipe diameter.

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KEYWORDS: Municipal water, water pipelines, Mathematical model, Model Verification, Water Distribution Systems

INTRODUCTION

Red water problems associated with release of iron in drinking water distribution systems have been reported for almost as long as iron pipes have been used to transport potable water. These water quality problems are mainly attributed to the corrosion process and the release of corrosion products as particulate and dissolved iron from unlined cast iron and galvanized iron pipes. Mutoti (2003) developed a flux model for the prediction of iron concentration in drinking water distribution systems. This model was developed mathematically, and empirically using a single finished water blend with fixed water chemistry and two single material pilot distribution systems: aged unlined cast iron pipe and aged galvanized pipe. This flux model allows prediction of iron concentration as a function of a flux term, K_m , pipe geometry (diameter and length), Reynolds Number and hydraulic retention time. This paper presents a verification of the flux model by comparing predicted and measured iron concentrations in fourteen independent hybrid pilot distributions systems. The hybrid pipe systems contain multiple (four) pipe materials in series. For the verification experiments, the hybrid lines received finished water inputs that exhibited significant variation in water chemistry. Examination of the model provides an insight into the factors that influence the flux term.

LITERATURE REVIEW

Flux Model

Mutoti (2003) applied two mathematical approaches to develop a flux model, (1) one-dimensional conservation of mass equation, and (2), reactor kinetics-type mass balance. Both approaches reduced to the following mathematical form, $[Fe] = 4K_m HRT / D$. In addition, pilot distribution experiments using the unlined and galvanized pipes confirmed the same mathematical relationship. A simplified mass balance approach used to generate the flux model is shown below:

Input - Output + Generation = Accumulation

$$QC_{in} - QC_{out} + K_m(SA) = 0 \quad (1)$$

$$C_{out} - C_{in} = \Delta C = \Delta[Fe] = \frac{K_m(SA)}{Q} \quad (2)$$

$$\Delta[Fe] = \frac{K_m \pi D L}{u \frac{\pi D^2}{4}} = \frac{4K_m L}{uD} = \frac{4K_m(HRT)}{D} \quad (3)$$

Furthermore, iron release is predominantly particulate and diffusion controlled processes, such as dissolution and corrosion, do not control iron concentration in drinking water distribution pipes (Mutoti 2003). For pipe systems that are composites of different pipe materials (hybrid systems), the total iron concentration is given by:

$$\Delta[Fe] = \sum_{i=1}^n \frac{4K_{mij}L_{ij}}{u_{ij}D_{ij}} \quad (4)$$

Mitigation of iron release in drinking water distribution systems therefore requires an understanding of the extent to which each of the parameters in Equation 3 impacts iron release, as well as the dynamics of the flux term.

Pipe Geometry

The relevant pipe attributes includes parameters that influence surface area (pipe diameter and length). However, the length and diameter of each link may be different. It is therefore important to know the total length of links of the same material. While in actual distribution systems the exact pipe diameters, and lengths may be difficult to know for sure, iron release can be calculated based on the assumption that the number of links, lengths and diameters in a hybrid system are known and fixed. Higher iron concentrations are expected in smaller diameter pipes (of the same material) due to their larger surface area to volume ratio compared to larger diameter pipes.

Flow velocity

Flow velocities in drinking water distribution pipes can vary between 0 to 3.048 m/s. The flow velocity and pipe length

together define the hydraulic retention time (water age) for a given pipe link.

Impact of Water Chemistry on Iron Release

In the United States, the majority of distribution systems are comprised of iron pipes. Other pipe materials commonly found in distribution pipes include lined cast iron and polyvinyl chloride (PVC). The release of corrosion products into the bulk water depends on the nature and size of corrosion products existing on each pipe material. Corrosion of cast iron pipes represents the most common drinking water distribution system complaint (McNeill and Edwards 2001).

Many water quality parameters affecting iron release may influence the flux term. Sander et al (1996) investigated the effect of pH, calcium and bicarbonate on iron corrosion in drinking water distribution systems and concluded that corrosion rates depend on calcium concentration at low total carbonate but not at high total carbonate concentration. Rushing et al (2003) found that silica enhanced iron release. Savoye et al (2001) report that pH and some anion species, notably chloride, sulfate and/or carbonate affected general corrosion/passivity transition of iron. Chlorides and sulfates are reported to be the main aggressive constituents present in water. In a general survey of the literature, the effects of pH, alkalinity, buffer intensity

and dissolved oxygen on iron pipe corrosion in distribution systems are generally acknowledged. McNeill and Edwards (2001) noted that most of the studies are however not representative of conditions within the distribution system. Despite the different views by many researchers on iron release in drinking water distribution systems, there is a general consensus that increased pH, buffer intensity, alkalinity, and dissolved oxygen all result in decreased red water complaints. Some parameters have opposing effects depending on the mechanism at play, for example, oxygen increases the rate of corrosion, which results in the formation of a protective passive layer that in turns slows the diffusion rate of oxygen to the metal surface, thus retarding the corrosion process (Sarin et al. 2004). Flow velocity has been shown (Jones 1996) to increase corrosion rate as it increases the rate of oxygen supply for the corrosion reaction. Clement et al. (2002) report that at oxygen greater than 1 mg/L, increasing oxygen concentration has no effect on the rate of corrosion. In contrast, anaerobic environments may be associated with increased iron concentration. Excessive velocities may scour away the protective layer (McNeill and Edwards 2001), leading to iron release by erosion. High turbidity spikes have been reported where stagnation conditions exist (Sarin et al. 2003).

Corrosion indices, notably the Langelier stability index (LSI) and the Larson ratio combine the effects of multiple water quality parameters to assess the tendencies of different waters to corrode iron pipes surfaces. Pisigan and Singley (1987) discourage the use of LSI index as an indicator of iron release in drinking water distribution system. The Larson index however appears to agree with current findings i.e. adverse effects of sulfates and chlorides and mitigating effects of dissolved inorganic carbon. (Imran et al. 2005), developed an empirical statistical model, that gives a wider view of the effects of water chemistry on corrosion product release.

$$\Delta Color (CPU) = \frac{[Cl^-]^{0.485} [SO_4^{2-}]^{0.118} [Na^+]^{0.561} [DO]^{0.967} [T]^{0.813} [HRT]^{0.836}}{20.9 [Alkalinity]^{0.912}} \quad (5)$$

In the above model, chemical concentrations are in milligram per liter, the hydraulic retention time (HRT) is in days, temperature, T is in degrees Celsius, and the predicted rise in color, $\Delta Color$ is in cobalt platinum units.

Flux term, K_m

Mutoti (2003) defined the flux term as the mass rate of iron release per unit surface area of interior pipe wall ($M/L^2.T$). Flux depends on pipe material and water chemistry. For a constant water quality, the flux was reported to be

constant under laminar conditions and to vary linearly with Reynolds Numbers under turbulent flow conditions, according to:

$$K_m = \beta_o + \beta_1 + (Re - 2000) \quad (6)$$

β_o and β_1 are parameter estimates that must be established for each pipe material and water quality. The flux was quantified using a fixed water chemistry produced from a fixed blend ratio of treated groundwater, surface water and desalinated water in aged unlined cast iron and galvanized pipes.

Dietz et al (2002) have shown that both color and turbidity are excellent surrogates for iron measurement in drinking water distribution systems. Color (or turbidity) change caused by changes in water chemistry can be accounted using Equation 5. Thus for a known flux ($K_{m(1)}$), at a known water chemistry (and therefore $Color_{(1)}$), a new flux ($K_{m(2)}$) for a different water quality (producing a $Color_{(2)}$) for the same pipe reach can be obtained using Equation 7.

$$K_{m(2)} = K_{m(1)} \times \frac{Color_{(2)}}{Color_{(1)}} \quad (7)$$

Blended finished water used for the flux experiments consisted of 60% groundwater, 30% surface water and 10% reverse

osmosis permeate. The relevant chemistry of the blended water is provided in Table 1.

Using Equation 5 and water quality data in Table 1 at a 5-day HRT, 7.5 mg/L DO and 20 °C, the predicted color release (ΔColor) is 9.34 cobalt-platinum units (CPU). Next, the correlation between iron and color was used to compute an equivalent iron concentration. The iron concentration corresponding to 9.34 CPU is 0.11 mg/L. This prediction is based on the unlined cast iron pipe geometry that was used for the flux experiments: 0.1524 m diameter, 26.3 m length.

The flux term is constant for Reynolds Numbers below 2000 and varies linearly with Reynolds Number above 2000 (Mutoti, 2003). This relationship is defined in Equations 8 and 9 for galvanized and unlined cast iron pipe, respectively.

$$K_m(\text{mg}/\text{m}^2 \cdot \text{d}) = 4.5 \times 10^{-3}(\text{Re} - 2000) + 1.99 \quad (8)$$

$$K_m(\text{mg}/\text{m}^2 \cdot \text{d}) = 9.0 \times 10^{-3}(\text{Re} - 2000) + 4.16 \quad (9)$$

EXPERIMENTAL DESIGN

Model verification was carried out at the pilot site in the Tampa Bay Water Authorities Cypress Creek Wellfield (Figure 1). Seven treatment processes were used to produce different water sources for blending as listed in Table 2. The different

sources produced finished water blends with very different chemical compositions.

Fourteen independent hybrid pilot distribution pipes receiving water with a significantly different chemistry from that used in the experiments for the development of the flux model (Table 1) were used for model verification. The pilot distribution system was continuously fed a fixed blend of finished water for 90 days, before switching to a different blend. During each 90-day period or phase, weekly samples were analyzed for the feed, outlet and intermediate sampling ports. In all, a total of four, 90-day phases were completed. Iron concentrations measured in the hybrid lines are compared with values predicted using the flux model (Equations 4, 5, and 7). In addition, various scenarios were simulated to determine the effects of pipe diameter, pipe length, flow rate and Reynolds Number on the release of iron in galvanized and unlined cast iron pilot distribution systems. The pipe geometries, feed source water blends, and feed rates for the verification experiments are reviewed in Table 3.

RESULTS: FLUX MODEL VERIFICATION

Average flux data for the single material pipes from phases 1 through IV are given in Table 4. This data is based one-year pilot distribution operation split into 90-day operational

phases. Within each phase, temperature and modest water quality variations were experienced. Finished water quality variations were more pronounced in the surface water, which varied markedly with season.

Flux values computed from the data generated in phase I through phase III indicate that the flux for PVC and lined cast iron pipes are negligible and can be regarded as zero for all practical purposes. The contributions of PVC and lined cast iron pipe reaches in the hybrid systems are therefore neglected for all iron concentration measurement and simulation purposes.

The average flux for unlined cast iron was $4.16 \text{ mg/m}^2\cdot\text{d}$ and agrees with the average flux of $4.21 \text{ mg/m}^2\cdot\text{d}$ obtained during phase I through phase IV. A flux of $1.99 \text{ mg/m}^2\cdot\text{d}$ for galvanized pipe was obtained during flux experiments. The different values for the average flux are specific to the two different pipe materials.

The measured and predicted total iron concentrations using the flux model are presented in Table 5 for 14 independent pilot distribution systems used to verify the model. The same information is presented in Figure 2 through Figure 5 for each phase of the study. Error bars are provided on these figures to indicate the maximum and minimum observations in each phase. The entire data set is presented in Figure 6 to provide an

assessment of the model accuracy when applied to the verification data set. As measured by the coefficient of determination (R-squared of 0.8), the model predictions provide an excellent match to the data. Under-predictions were observed for all values in phase IV. It is speculated that this systematic error may be attributed to a large temperature drop that was experienced during phase IV. The largest over-prediction or under-prediction occurred in the pilot distribution lines that received extreme concentrations for sulfates, chloride and/or alkalinity.

RESULTS: FLUX MODEL ANALYSIS

Impact of Reynolds Number on Iron Concentration

The impact of Reynolds Number on iron concentration is complicated by the interrelations among many factors, including pipe diameter and flow velocity (which is related to hydraulic retention time). Equations 10 and 11 were used to predict iron concentrations in a reach of unlined cast iron pipe under laminar and turbulent flow conditions, respectively.

$$\Delta[Fe] = \sum_1^n \left[\frac{4 \times 4.16 L_{ij}}{u_{ij} D_{ij}} \right] \quad (10)$$

$$\Delta[Fe] = \sum_1^n \left[\frac{4 \times (9 \times 10^{-3} (Re - 2000) + 4.16) \times L_{ij}}{u_{ij} D_{ij}} \right] \quad (11)$$

The effects of Reynolds Number on predicted iron concentrations are shown in Figure 7. This simulation was for a 6-inch (0.1524 m) diameter, 1-mile (1609 m) unlined cast iron pipe, under both laminar flow ($Re \leq 2000$) and turbulent ($Re > 2000$) flow conditions.

Under laminar flow conditions, flux is constant resulting in a large increase in iron concentrations as the Reynolds Number is reduced. This condition would correspond with long HRTs in dead zones in the distribution system. The simulated values for turbulent flow conditions would correspond with high velocities and reduced HRTs in the pipe reach. For these conditions, the flux would increase in proportion to the Reynolds Number per Equation 8, but the HRT would decrease by a similar proportion. The net effect on the iron concentration would be minimal, with a resulting concentration that exhibits little sensitivity to Reynolds Number under fully turbulent conditions. It is not implied that extreme velocities associated with unidirectional flushing would not produce a short-duration elevation in iron levels.

The transition region between laminar and turbulent conditions in Figure 7 is characterized by a minimum in iron concentration. As flows transition from laminar to a turbulent regime, it is accepted that definition of transport properties becomes complicated (e.g. Moody friction factor). The data set generated in this study is much more extensive in the laminar region than for transition or turbulent conditions. This bias in

experimental effort is consistent with a desire to investigate conditions that would produce worst case iron levels. Accordingly, a greater confidence would be justified for the simulations in Figure 7 that correspond with laminar flow. Further investigations would be desired to confidently evaluate flux under transitional or turbulent flow conditions. However, this data limitation does not detract from the utility of the results to describe worst-case (laminar) results.

In addition, Figure 7 also illustrates the impact of water chemistry, which supports earlier observations that high sulfate/chloride and/or low alkalinity waters (desalination and enhanced treatment surface water, respectively) may lead to higher iron release. Similar plots may be obtained for galvanized iron pipe, with lower iron concentrations due to the lower flux.

The differences between unlined cast iron pipe and galvanized iron under laminar flow conditions are depicted in Figure 8.

Flux Model Analysis: Impact of Pipe Diameter

The impact of pipe diameter on iron concentration under laminar and turbulent flow conditions is presented in Figure 9 and Figure 10, respectively. These simulations are for 1609 m (1 mile) of unlined cast iron and the same length for galvanized pipe. Iron concentration is inversely proportional to pipe

diameter, i.e., for a large diameter pipe, the relative increase in iron concentration is reduced in comparison to a smaller diameter pipe. The phenomenon is best explained by considering the geometry ratio, surface area to volume, which reduces to $4/D$. Thus as pipe diameter, D increases, $4/D$ decreases, resulting in more red water problems in smaller diameter pipes. A smaller rise in iron concentration is observed, however in the 2-inch galvanized iron pipes compared to the 6-inch unlined cast iron pipe and this is attributed to pipe material (unlined cast iron has larger flux compared to the galvanized iron pipes).

Although the pipe diameter is known at the design stage, the true pipe diameter is not fixed and varies with pipe age and the quality of water transported. The main reason for this variation in pipe diameter is the formation of tubercles, an internal growth of corrosion products. Simulation results are however consistent with expected trends, with two orders of magnitude higher simulated iron concentrations under laminar compared to turbulent flow conditions.

Flux Model Analysis: Impact of Pipe Length

For a fixed set of hydraulic and water chemistry conditions, it is intuitive that iron concentration increases linearly with increasing pipe length. This effect can be confirmed with the flux model equations.

CONCLUSIONS

While the mathematical integrity of the flux model was clearly supported by two approaches, the same form of the model was confirmed empirically, via flux experiments. Using an independent set of pilot data, a high prediction accuracy of the flux model was confirmed by a coefficient of determination, R^2 of 0.8. Flux term adjustment to account for changes in water chemistry can be accomplished with knowledge of relevant water quality parameters, thus avoiding flux term determination each time new water chemistry is introduced. The procedure permits adjustment of the flux value for hydraulic conditions (i.e. Reynolds Number) in addition to water quality. The analysis also incorporates pipe material and geometry (diameter and length) into the prediction of distribution system iron concentration.

A summation of iron released from individual reaches of pipes is required when applying the flux model to the hybrid systems. Iron released from PVC and lined cast iron pipes can be neglected for all practical purposes.

The Reynolds Number has an impact on the release of iron. The model simulations indicate that iron concentrations under stagnant to laminar flow conditions may be one to two orders of magnitude higher compared to iron concentrations under turbulent

flow conditions. In those situations where dead zones (and associated laminar flow conditions) can not be eliminated in a distribution system, control of water chemistry is the key to avoidance of red water episodes. The results of the simulations also indicate that where flushing is feasible, regulation of the hydraulic conditions to produce turbulent flow would also be effective to address elevated iron conditions.

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NOTATIONS

The following symbols are used in this paper:

D is the pipe diameter

HRT is the hydraulic retention time

ij denotes pipe link node

K_m is a pipe material specific flux term

L_{ij} is length of pipe link ij

Q is flow rate (or flow velocity times pipe area)

SA is pipe reach internal surface

T is the temperature in degrees Celsius

u_{ij} is flow velocity in the link ij

Δ Color is change in color, measured in cobalt-platinum
units

$\Delta[Fe]$ is released iron concentration

Re is Reynolds number

Table 1 Flux Experiment Feed Water Quality, K_m (1)

Table 2 Mode of production of simulated source waters

Table 3 Hybrid PDS Geometries, Feed Sources and Blend Ratios

Table 4 Pipe Material Fluxes ($\text{mg}/\text{m}^2\cdot\text{d}$), Phase I -IV ($\text{Re} < 2000$)

Table 5 Hybrid PDS Measured and Flux Model Predicted Iron
Concentrations

Figure 1 Pilot Treatment and Distribution Systems used for model
verification

Figure 2 Phase 1 Measured Versus Predicted Total Iron
Concentrations

Figure 3 Phase II Measured Versus Predicted Total Iron
Concentrations

Figure 4 Phase III Measured Versus Predicted Total Iron
Concentrations

Figure 5 Phase IV Measured Versus Predicted Total Iron
Concentrations

Figure 6 Measured versus Predicted Iron Concentrations in Hybrid
PDSs

Figure 7 Predicted Iron Concentration, Unlined Cast Iron Pipe,
Laminar and Turbulent Flow Conditions

Figure 8 Predicted Iron Concentration under Laminar Flow
Conditions

Figure 9 Impact of Pipe Diameter under Laminar Flow Conditions

Figure 10 Impact of Diameter under Turbulent Flow Conditions

Turbidity	Total	Ca ²⁺	Mg ²⁺	Silica	Na ⁺	pH	Alkalinity	TDS	Cl ⁻	SO ₄ ²⁻
(NTU)	Fe	(mg/L)	(mg/L)	(mg/L)	(mg/L)	s.u	(mg/L as CaCO ₃)	(mg/L)	(mg/L)	(mg/L)
0.306	0.045	68	6.4	9	31	7.96	148	377	38	66

Note: All measurement units are in mg/L, unless stated.

Source waters	Method of Production
GW	Aeration of raw groundwater representing historical groundwater usage
SW	Ozonation and subsequent treatment with biological activated carbon (BAC) 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 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 GW,

	SW, and RO waters
G4	Nanofiltration of blend of GW, SW, and RO waters
S2	Nanofiltration of Hillsborough river surface water coagulated with ferric sulfate, settled and filtered
RO-1	Reverse osmosis permeate of
RO-2	groundwater with controlled additions of alkalinity, chlorides and sulfates for
RO-3	verification of empirical model and resolution of confounding effects.

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

PDS	PVC	LCI	UCI	GI	Sources (%)	
	(m)	(m)	(m)	(m)	Phase I & III	Phase II & IV
01	5.87	5.94	3.58	12.5	G1-100	G2-100
02	5.87	5.13	3.58	12.5	G2-100	G1-100
03	5.87	5.79	3.58	12.0	S1-100	S2-100
04	5.87	5.13	3.58	12.5	G4-100	G4-100
05	5.87	5.13	3.58	12.5	RO-100	S1-100
06	5.87	5.66	3.58	12.4	G1-55, S1-45	G1-68, RO-32
07	5.87	5.13	3.58	12.5	G1-68, RO-32	G1-55, S1-45
08	5.87	5.51	3.58	12.5	G1-23, S1-45, RO-32	G1-60, S2-30, RO-10
09	5.87	5.66	3.58	12.4	G1-60, S2-30, RO-10	G1-23, S1-45, RO-32
10	5.87	5.13	3.58	12.5	G2-50, S1-50	G2-62, S1-24, RO-14
11	5.87	5.54	3.58	12.2	G2-62, S1-24, RO-14	G2-50, S1-50
12	5.87	5.41	3.58	12.6	G3-100	G3-100
13	5.87	5.41	3.58	12.6	S2-100	RO-100
14	5.87	5.94	3.58	12.7	G1-70, S1-30, RO-0	G1-70, S1-30, RO-0

PHASE	Unlined Cast		Lined Cast		Galvanized
		Iron	PVC	Iron	Iron
I (5d)		3.84	0.04	0.01	0.30
II (5d)		2.93	0.06	-0.03	0.27
III (5d)		3.65	-0.02	-0.02	0.23
III (2d)		5.62	-0.18	-0.05	1.34
IV (2d)		5.02	-0.069	-0.16	0.73

Measured Iron (mg/L)					Model Predicted Iron (mg/L)			
Phase					Phase			
PDS	I	II	III	IV	I	II	III	IV
1	0.05	0.12	0.03	0.04	0.05	0.09	0.05	0.01
2	0.12	0.06	0.10	0.03	0.09	0.05	0.06	0.01
3	0.44	0.40	0.67	0.23	0.58	0.39	0.55	0.13
4	0.25	0.38	0.18	0.14	0.21	0.32	0.22	0.05
5	0.29	0.65	0.42	0.44	0.34	0.44	0.47	0.15
6	0.10	0.19	0.19	0.08	0.24	0.13	0.14	0.03
7	0.26	0.51	0.24	0.07	0.24	0.35	0.27	0.03
8	0.42	0.22	0.34	0.09	0.42	0.17	0.27	0.03
9	0.06	0.18	0.10	0.05	0.05	0.11	0.11	0.02
10	0.31	0.45	0.26	0.20	0.30	0.29	0.27	0.09
11	0.29	0.41	0.31	0.20	0.32	0.29	0.27	0.06
12	0.60	0.36	0.61	0.18	0.80	0.28	0.61	0.09
13	0.33	0.52	0.44	0.31	0.35	0.44	0.45	0.15
14	0.22	0.22	0.14	0.08	0.23	0.15	0.12	0.05

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