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DEVELOPMENT OF A NOVEL DISTRIBUTION SYSTEM IRON RELEASE FLUX MODEL

ABSTRACT

Despite red water being one of the largest consumer water quality complaint categories, none of the models available to date can adequately address iron release in drinking water distribution systems. This is due to the complex nature of iron sources, iron release mechanisms, often conflicting impacts of various physio-chemical and biological factors, pipe material and age and the cocktails of corrosion products released. This paper presents a mathematical and pilot-scale empirical development and quantification of a unique zero-order Flux model. Iron concentration was found to depend **on surface release** flux (K_m), pipe material, pipe geometry and hydraulic retention time. Flux is a function of pipe material, water chemistry and Reynolds Number. In the galvanized iron, K_m (mg Fe/m²-d) has values of 1.99 and $0.0045(\text{Re} - 2000) + 1.99$ under laminar and turbulent flow conditions, respectively. Similarly, K_m was found to be 4.16 and $0.009(\text{Re} - 2000) + 4.16$ for unlined cast iron pipe under laminar and turbulent flow conditions respectively.

INTRODUCTION

The occurrence of red water in distribution systems remains the most common water quality consumer complaint. The main sources of iron in drinking water are raw water, treatment processes that use iron, and iron released in distribution systems. While raw water and treatment processes can be controlled easily, iron due to release in distribution system is complex. Development of an iron concentration prediction model for drinking water distribution systems may provide a practical tool that could help understand the occurrence of red water and ways to mitigate those occurrences. In drinking water distribution systems, two processes are

generally accepted as sources of iron; (1) corrosion and (2) dissolution of corrosion scales. Corrosion, an electrochemical process results in direct release of iron (II) into water and formation of iron scales. Corrosion scales slow down the corrosion process and the release of dissolved iron. Dissolution of corrosion scales is a diffusion equilibrium controlled process that results in the release of dissolved iron. Several views on iron release mechanisms and specific theoretical and empirical models have also been postulated. Unfortunately, existing approaches significantly under-predict iron concentrations typically observed in many distribution systems. This paper describes the development of an alternative approach that is supported by both mathematical derivations and empirical observations. In addition to corrosion and dissolution, this model takes into account factors responsible for iron release such as water chemistry, temperature, pipe material, pipe geometry (diameter and length), and hydraulic conditions using a non-mechanistic approach. Similar models have been widely used to describe disinfectant decay in drinking water distribution systems. There is significant amount of literature on water stability and corrosion, notably the development of calcium carbonate-based stability indices, such as the Langelier index, Ryznar index, and calcium carbonate precipitation potential.

Water quality modeling. Water quality modeling involves tracking the generation, decay and propagation of conservative and non-conservative parameters based on three principles: (1) mass conservation within differential pipes lengths, (2) complete and instantaneous mixing of water entering junctions, and (3) application of appropriate material, growth and decay kinetics (Clark et al, 1998). Conservative parameters do not undergo physical and chemical changes while non-conservative or reactive parameters (e.g. chlorine residual) undergo chemical change. Initial modeling efforts produced steady-state models that define spatial distribution of water quality parameters along with their travel paths and travel time under

a given set of loading conditions (Boulos et al, 1994). Steady-state models have since evolved to dynamic models that simulate time variation of contaminants and other distribution system variables. Boulos et al (1994) gave a detailed description of water quality models including network models, steady-state models, dynamic models, contaminant propagation models, and numerical models.

The concentration of a solute in pipes can be accurately described using three dispersion component terms (1) molecular diffusion, (2) turbulent diffusion and (3) longitudinal shear flow. The latter is in the order of a million times greater than the first two. Molecular and turbulent diffusion lead to a Gaussian-type distribution of the contaminant along the pipe length. The resulting classical one-dimensional advection dispersion model (1) has been used to describe contaminant propagation (Baeumer et al, 2001).

$$\frac{\partial C_{(t,x)ij}}{\partial t} = -u_{ij} \frac{\partial C_{(t,x)ij}}{\partial x} + D \frac{\partial^2 C_{(t,x)ij}}{\partial x^2} \quad (1)$$

The terms in equation 1 are defined as; $C_{(t,x)ij}$ = concentration (M/L^3), x = location along the pipe length, t = time at location x , ij = link between nodes i , and j ; u_{ij} = link's flow velocity (L/T), D = the combined effect of molecular and advection dispersion (L^2/T).

Liou and Kroon, 1987; Grayman et al, 1988, Boulos et al, 1994; Rossman et al, 1994; Clark and Grayman, 1998 and Walski et al, 2001 have given variations of the advection dispersion equation neglecting the effects of the Taylor diffusion $\partial^2 C_{(t,x)ij} / \partial x^2$ and instead, including a contaminant generation/decay term ($k_{ij} C_{(t,x)ij}$) as:

$$\frac{\partial C_{(t,x)ij}}{\partial t} = -u_{ij} \frac{\partial C_{(t,x)ij}}{\partial x} + k_{ij} C_{(t,x)ij} \quad (2)$$

where, k_{ij} = the first-order rate constant within the link (T^{-1}).

Various numerical methods have been used to solve contaminant propagation equations for distribution networks. However, Lagrangian time driven method has been extensively used for water quality modeling (Rossman et al 1993).

Modeling to Date. The first-order decay model, equation 3, is most widely used to describe the combined effects of the wall and liquid phase reactions on chlorine dissipation in drinking water distribution systems (Walski et al 2001):

$$C_t = C_o e^{-K \Delta t} \quad (3)$$

The terms in equation 3 are defined as; C_t = concentration (M/L^3) at time Δt , C_o = initial concentration (M/L^3) of the substance, K = overall rate constant ($1/T$). The overall rate constant incorporates the bulk liquid rate constant, the wall reaction, mass transfer coefficient and pipe diameter, and Δt = hydraulic retention time (T). Despite the wide use of the first-order decay/growth model for modeling distribution system chlorine decay, it has not been successfully and widely used modeling iron release.

Distribution System Iron. Maintaining low iron concentrations in drinking water distribution systems is complicated by the many potential iron sources (raw water, ferric coagulation for surface waters, iron pipe corrosion) and release mechanisms (corrosion product solubility and film release). There are conflicting views on the exact mechanism of iron release, with some authors (Kuch 1988; Pisigan and Singley, 1987) suggesting direct release from corrosion processes. Sander et al (1996, 1997) state that iron release bears no simple relation to the rate of iron corrosion and emphasized the need to distinguish between red water problems and corrosion rates, suggesting that corrosion related water quality problems are mainly a

function of the precipitation and dissolution properties of corrosion scales formed. Thus, red water quality problems do not depend primarily on corrosion process, but on a large reservoir of corrosion product layers making it necessary to model scale behavior. It is however important to note that corrosion, an electrochemical thermodynamic process, ultimately is the initial source of corrosion related iron within the water supply system. Although pitting corrosion **can** be responsible for pipe failure, it is **the release of particulate iron from corrosion scales or passive layers** that is of most concern to drinking water quality and red water problem. Passive layer solubility and film release processes predominantly contribute to the total iron concentration causing red water problems. Paradoxically, formation of ferric and ferrous passive layers retards the rate of corrosion (Uhlig **and** Revie, 1985). Snoeyink **and** Jenkins (1980) describe in detail the chemistry of rust formation from iron (II) to ferric hydroxide dehydration and siderite, $\text{FeCO}_{3(s)}$ in the presence of bicarbonate alkalinity.

Several corrosion studies (Taylor et al, 2005, Kuch 1988; Sander et al 1997; Sarin et al 2001, and Lin et al 2001) have identified goethite ($\alpha\text{-FeOOH}$), lepidocrocite ($\gamma\text{-FeOOH}$), magnetite (Fe_3O_4), siderite (FeCO_3), ferric hydroxide ($\text{Fe}(\text{OH})_3$), ferrous hydroxide ($\text{Fe}(\text{OH})_2$), and calcium carbonate (CaCO_3) as species commonly found within the passive layers. Dissolved iron from the passive layers is controlled by the solubility of the solid species, available pipe surface area, flow velocity and the concentration gradient between the pipe water and bulk liquid. Clement et al, (2002), suggest that siderite controls the concentration of dissolved ferrous ion in water due to its higher solubility product. However the siderite model **under-predicts** the total iron concentration found in drinking water distribution systems (**Taylor, 2005**) leading to speculations that mechanisms other than dissolution govern iron release in distribution systems.

The impact of various water chemistry parameters on corrosion products, notably chlorides, sulfates and dissolved carbon is well documented in literature (Imran et al 2005, Sander et al 1996, 1997, Rushing et al 2002). Sander et al (1997) concluded that at low total carbonate concentration, corrosion rate depends on calcium concentration whereas no such dependence is observed at high total carbonate concentration. Savoye et al (2001) suggest that the general corrosion to passivation transition of iron is mainly affected by pH as well as some anion species such as chloride, sulfate and carbonate. McNeill and Edwards (2001) reviewed the effects of pH, alkalinity, buffer intensity and dissolved oxygen on iron release and concluded that most of the studies are not reflective of conditions within the distribution system. Despite the conflicting views among various authors, there is however some general agreement that increased pH, buffer intensity, alkalinity and dissolved oxygen all lead to decreased red water complaints. In contrast, coupon weight loss experiments have shown that elevated dissolved oxygen results in increased corrosion rates. Flow velocity has been shown to increase corrosion rate at high dissolved oxygen levels, possibly due to scouring of protective layer at excessively high velocities, (McNeill and Edwards, 2001). Stagnation has been associated with high turbidity spikes especially at night (Sarin et al, 2001, van Rijsbergen et al, 1998).

Complex physio-chemical and biological interactions within the pipe system lead to the release of iron from iron metal and passive corrosion layers mostly in particle form. Figure 1 presents data from this study which clearly shows that total iron released increases with time while the concentration of dissolved iron is nearly constant and below the dissolved iron concentration predicted by FeCO_3 solubility at maximum bicarbonate concentration of 1×10^{-5} moles per liter. Figure 1 suggests the release of particulates from corrosion scales that is

independent of the concentration gradient. A different approach is therefore required to predict total iron concentration in drinking water pipe networks.

Figure 1 Change in Iron Concentration with Hydraulic Retention Time

Objectives. This paper presents a new model for the prediction of the concentration of iron in corroded drinking water pipe networks. This model is supported by empirical pilot-scale distribution system data and is derived here using two mathematical approaches. This theoretical model forms the basis for flux experiments used to develop an empirical model for iron concentration as a function of hydraulic conditions, pipe material and pipe geometry for fixed water chemistry. This work was based on a 3-year project **conducted by Taylor (2005) at the University of Central Florida and funded by the American Water Works Association Research Foundation-Tampa Bay Water.**

EXPERIMENTATION

The flux concept was developed from two mathematical approaches, (1) the one-dimensional mass conservation differential equation, a form of the advective dissipation equation and (2) the mass balance approach. Pilot-scale flux experiments were designed to investigate the flux constant. The pilot-scale distribution system consisted of 18 parallel distribution systems (PDS): 14 hybrid lines and 4 single material lines receiving seven significantly different finished waters. The single material lines consisted of polyvinyl chloride (PVC), lined iron, unlined cast iron and galvanized iron pipes. The hybrid lines were made up of reaches of all four materials. All pipe materials were **old, and were** excavated from existing full-scale distribution system. Operating procedures (pumps and valves) allowed the delivery of the desired blend and desired flow rates to the different pilot distribution systems. A view of the site and a section of the pilot distribution system are shown in Figure 2.

Figure 2 Pilot Research Facility and the Pilot Distribution Systems

Twelve months average data presented in Figure 3 indicates that for PVC and lined cast iron pipes, corrosion-related water quality deterioration is negligible and could be ignored for all practical purposes (Dietz et al, 2002).

Figure 3 Average Effluent Iron Concentrations for Single material PDS Pipes

Normal Pilot-Distribution Operations. Pilot distribution systems were initially (Phase I to III, 12/8/01 to 8/30/02) operated at a 5-day hydraulic retention time (HRT) to simulate dead zone conditions. The HRT was changed to 2 days during the final two weeks of Phase III through Phase V (8/31/02 to 4/4/03) to facilitate maintenance of a 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 and once every two weeks for the 2-day HRT period. The flush velocity was 0.3 m/s (1 ft/s) using a minimum of 3-pipe volumes of water. Sampling was done once a week at the influent and effluent standpipes and analyzed for a number of water quality parameters.

Flux Experiments. Normal operation of the pilot distribution systems was limited to extremely small velocities in order to achieve the desired hydraulic residence times (two or five days). Consequently, the database developed from normal PDS operation was not suitable for evaluation of the effect of variant hydraulic conditions (based on Reynolds Number) on the iron flux values. A series of experiments were completed to investigate the effect of Reynolds Number on the flux values. The flux experiments were carried out by feeding a blend of treated water sources at selected Reynolds Numbers. These experiments were conducted using the 0.1524 m (6 inch) diameter, 26.3 m (86.3 ft) long PDS 15 (unlined cast iron) and the, 0.0508 m (2 inch) diameter, 38.3 m (125.67 ft) long PDS 18 (galvanized) to define values for each pipe

material. Each flux experiment was conducted using 4.54 m³ (1,200 gallons) of blended finished water. This volume was sufficient to flush the pipe contents with 9.5 pipe volumes of fresh blend. The blend consisted of 60% GW - conventionally-treated groundwater, 30% SW - enhanced treated surface water, and 10% RO - desalinated water. Relevant water chemistry data for the blend used in the flux experiment is provided in Table 1. The feed and outlet water quality were measured to determine the change in color and turbidity at various time intervals.

Table 1 Average Feed and Output Water Chemistry

RESULTS

Flux model derivation - Advective Dispersion Equation Approach. The generation term in the one-dimensional mass conservation (equation 2) was modified to $K_m(SA/V)$ and the result is equation 4:

$$\frac{\partial C_{(t,x)}}{\partial t} = -\left(\frac{Q}{A}\right) \frac{\partial C_{(t,x)}}{\partial x} + K_m \left(\frac{SA}{V}\right) \quad (4)$$

In the above equation, t = time (T), A = pipe cross sectional area, (L²), SA = pipe internal surface area, (L²), Q is the flow rate (L³/T), V = pipe volume (L³), and K_m = flux (M/L².T). The geometric ratios in equation 4 can be reduced to $\frac{SA}{V} = \frac{\pi DL}{\pi D^2 L/4} = \frac{4}{D}$ and $\frac{Q}{A} = u$, respectively. Where D = pipe diameter (L), u = flow velocity (L/T)

For known initial conditions and assuming steady state, the closed solution for equation 4 is obtained as follows:

Assuming Steady State:

$$\text{i.e. } \frac{\delta C(x, t)}{\delta t} = 0 \quad \text{and} \quad \frac{\delta C(x, t)}{\delta x} = \frac{dC}{dx} \quad (5)$$

$$\therefore 0 = -\frac{Q}{A} \frac{dC}{dx} + K_m \frac{SA}{V} \Leftrightarrow u \frac{dC}{dx} = K_m \frac{SA}{V} \quad (6)$$

However, distance traveled is equal to velocity multiplied by time (i.e. $dx = udt$).

Thus, substituting for dx in equation 6 gives:

$$u \frac{dC}{dx} = K_m \frac{SA}{V} \Leftrightarrow dC = K_m \frac{SA}{V} dt \quad (7)$$

The surface area to volume ratio ($SA/V = \pi DL / \pi D^2 L / 4$) in equation 7 reduces to $4/D$ and integrated to obtain equation 9.

$$\int_{C_o}^{C_t} dC = \frac{4K_m}{D} \int_{t_o}^t dt \quad (8)$$

$$\Rightarrow C_t - C_o = \frac{4K_m(t - t_o)}{D} \quad (9)$$

The terms in equation 9 are defined as; C_o is the initial concentration (M/L^3) at time t_o , C_t = concentration (M/L^3) at time t , $(t - t_o)$ = hydraulic retention time, HRT (T).

The increase in iron concentration, $\Delta[Fe] = (C_t - C_o)$ is defined in equation 10.

$$\Delta [Fe] = \frac{4K_m HRT}{D} = \frac{4K_m L}{u D} \quad (10)$$

Equation 10 is a zero-order kinetic model with respect to iron concentration. Thus the increase in iron concentration is independent of the bulk phase iron concentration or concentration gradient between the bulk liquid phase and the concentration at the wall (as is the

case with dissolution). The increase in iron concentration however depends on the flux (K_m), pipe diameter, and hydraulic retention time. Implied in equation 10 is the inverse relationship between the increase in iron concentration and the fluid velocity and the intuitive increase in iron concentration with increasing pipe length.

Flux model derivation-Steady-State Mass Balance Approach. A pipe reach is essentially a plug flow reactor. Applying a mass balance (equation 11) around the pipe reach, and solving for the change in concentration, (equations 12 through 14) yield equation 15.

$$\text{Input} - \text{Output} + \text{Generation} = \text{Accumulation} \quad (11)$$

$$Q C_{in} - Q C_{out} + K_m SA = 0 \quad (12)$$

$$(C_{out} - C_{in}) = \Delta C = \frac{K_m SA}{Q} \quad (13)$$

$$\Delta C = \Delta[\text{Fe}] = \frac{K_m \pi DL}{u (\pi D^2/4)} \quad (14)$$

$$\Delta [\text{Fe}] = \frac{4 K_m L}{u D} = \frac{4 K_m \text{HRT}}{D} \quad (15)$$

Equations 10 and 15 are essentially identical, thus confirming the mathematical integrity of the flux model. K_m in the model is a mass rate per unit area term ($\text{M.L}^{-2}.\text{T}^{-1}$).

Flux K_m Determination. The usefulness the flux model depends on knowing the flux term, K_m . Intuitively, the flux term is a function of water chemistry (WQ) and hydraulic conditions within the pipe. Clement et al (2002) provide a more detailed discussion of the roles of some of the water quality parameters that may account for the effect of water chemistry on iron release (red water). Imran et al (2005) applied a statistical variable selection approach to

over 70 averaged data sets from the AWWARF-TBW project to define following empirical model in hybrid lines:

$$\Delta C \text{ (CPU)} = \frac{[Cl^-]^{0.485} [SO_4^{2-}]^{0.118} [Na^+]^{0.561} [DO]^{0.967} T^{0.813} HRT^{0.836}}{20.9411 [Alkalinity]^{0.912}} \quad (16)$$

At very high flow velocities, release of particulates may result from scouring action. The dimensionless Reynolds Number (Re), defined in equation 17 has been traditionally used to characterize hydraulic conditions with conduits as laminar ($Re < 2000$) or turbulent ($Re > 2000$).

$$Re = \frac{u \rho D}{\mu} = \frac{u D}{\nu} \quad (17)$$

In which, u = flow velocity (L/T), D = pipe diameter (L), μ is the absolute viscosity (M/L.T). The kinematic viscosity ν is the ratio of absolute viscosity to density, (L^2/T).

Flux, K_m as a function of water chemistry and hydraulic conditions can be determined by combining water chemistry effects, equation 16 and Reynolds Number, Re , (i.e. $K_m = f(WQ, Re)$) as shown in the full effects interactive model, equation 18 .

$$K_m = \beta_0 + \beta_1 (WQ) + \beta_2 (Re) + \beta_3 (WQ) \times Re \quad (18)$$

The parameter estimates β_0 , β_1 , β_2 and β_3 are dependent on water chemistry (WQ). Thus, at fixed water chemistry, equation 18 reduces to equation 19.

$$K_m = \alpha + \beta Re \quad (19)$$

Equation 16 presents an opportunity to adjust the flux term for variations in water chemistry, if the parameters in equation 16 are known for the new water source or blend. Equation 20 may be used to account for changes in water chemistry.

$$K_{m2} = K_{m1} \frac{\Delta C_2}{\Delta C_1} \quad (20)$$

In which, ΔC_1 and K_{m1} are the predicted color and flux at the original water chemistry and ΔC_2 is the predicted color change at the new source water chemistry given by equation 16.

Flux experiments were thus conducted at fixed water chemistry (Table 1) at selected Reynolds Numbers in order to determine alpha (α) and beta (β) in equation 19. The change in iron concentration (or a surrogate - turbidity or color) was required to calculate the flux term for a given Reynolds Number and water chemistry. Turbidity was shown to be more sensitive than color and to correlate well with particulate iron (Figure 4).

$$\Delta[\text{Fe}] \mu\text{g/L} = 7.3 \times 10^{-3} (\Delta \text{Turbidity (NTU)}) \quad (21)$$

This relationship was used to adjust the flux term, when water chemistry changed.

Figure 4 Correlations between Iron and Turbidity

Flux Experiment Results. Characteristic response curves, (Figure 5) were generated for each flux experiment and showed an initial increase in turbidity to a maximum value, followed by a decline to a steady-state value that was characteristic of each flow rate. Three pipe-volumes of fresh feed were required before steady-state turbidity values could be established.

Figure 5 Time Series Response of Turbidity during Flux Experiment

Flux Calculation. Average influent and effluent turbidity values were significantly different from each other based on T-statistics. Thus the steady-state difference between average effluent and average influent was used to estimate the change in iron concentration. Using the above information, flow rate and pipe geometry, the flux values were calculated for each experiment.

$$K_m = \frac{\Delta [\text{Fe}] \times \text{Flow}}{\text{Surface Area}} = \frac{\Delta \text{ntu}/0.0073 \times \text{Flow}}{\text{Surface Area}} \quad (22)$$

Table 2 and Table 3 report flux experiment data for the unlined cast iron and galvanized steel pipes, respectively. The data include the Reynolds Number at which experiments were conducted, the flow velocity, hydraulic retention time, average change in turbidity, calculated corresponding change in iron concentration (equation 21), and calculated flux values (equation 22). The calculated flux values for the unlined cast iron and galvanized steel are presented as a function of Reynolds Number in Figure 6.

Figure 6 Flux as a Function of Reynolds Number: All Experiments considered

Although a good linear relation was obtained when all experimental flux values are considered, a semi-log plot, (Figure 7) reveals subtle but more useful details about the relation between flux and Reynolds Number.

Figure 7 Flux –Log Reynolds Number Plot

A distinct change in the flux -Reynolds Number relationship was observed at Reynolds Number equal to 2000. The point coincides with the traditional cut point definition of a laminar flow regime. Thus a different relation exists between Reynolds Number and Flux under laminar flow conditions than under turbulent flow conditions. To correctly describe this relationship, a piecewise model is appropriate. One relation is used to represent constant flux under laminar flow, and a second linear relation under turbulent flow conditions. Figure 8 gives a generalized flux behavior as a function of Reynolds Number under both laminar and turbulent flow conditions.

Figure 8 Flux, (K_m) Behavior for all Laminar and Turbulent Flow Conditions

The mean flux values for both the galvanized steel and unlined cast iron pipes under laminar flow ($0 < Re \leq 2000$) and turbulent ($Re \geq 2000$) are given in Table 4. The best fit models for Reynolds Numbers greater than 2000 were found by a linear regression that was constrained to force the flux value to equal the average constant flux values obtained for the laminar flow when the Reynolds Numbers equal or less than 2000.

Table 4 Flux models Under Turbulent Flow (Fixed Water Chemistry)

The flux of corrosion product under laminar flow are constant and very small compared to the values of corrosion rate reported by Uhlig et al (1985) of $10 \text{ g/m}^2\cdot\text{day}$ ($0.929 \text{ g/ft}^2\cdot\text{day}$) for fresh iron surface and $1.0 - 2.5 \text{ g/m}^2\cdot\text{day}$ ($0.0929 - 0.2323 \text{ g/ft}^2\cdot\text{day}$) for passive layer protected surfaces. Under comparable hydraulic conditions, corrosion rates in galvanized are lower than those in unlined cast iron. For practical utilization, an assembly of equations derived above could be applied in aged pipe network with different pipe materials, pipe diameters and pipe lengths to predict the increase in iron concentration using equation 23.

$$\Delta[\text{Fe}] = \sum_1^m \left[\frac{4 K_{m(2)ij} L_{ij}}{u_{ij} D_{ij}} \right]_{\text{UnlinedCastIron}} + \sum_1^n \left[\frac{4 K_{m(2)kl} L_{kl}}{u_{kl} D_{kl}} \right]_{\text{Galvanized}} \quad (23)$$

Limitations. The experimental data to support development of the flux model were limited by available pipe materials and water quantities. The pipes were excavated from different locations within the distribution system and transported to a remote site for reassembly into the pilot distribution system. In order to facilitate determination of effects of variant water quality, all pipe of a given material was harvested from the same location. This approach limited the pipe to a single diameter and age for each pipe material. Surface water was hauled to the experimental site, imposing a constraint on the quantity of water that was available to permit conduct of long-duration experiments at elevated Reynolds Numbers. However, the water age

and hydraulic conditions represented by the bulk of the data are equivalent to problematic long HRT, near dead zones in real systems. In addition, the empirical water quality model is based on a wide range of water chemistries and temperature conditions. It is hoped that the general application of this flux model can be tested by utilities with independent data obtained for systems with a broader range of pipe diameters, pipe condition, and hydraulic conditions (Reynolds Number and HRT).

CONCLUSIONS

1. In aged corroded water distribution systems pipes, particulate iron is the predominant form of iron. Furthermore, diffusion controlled processes (such as equilibrium solubility) did not significantly influence the total iron concentration in the distribution system.
2. The release of iron in drinking water distribution systems are dominated by film release mechanisms.
3. The mass balance and the one-dimensional partial differential equation approaches both produce the same zero-order flux model.
4. The flux model can be used to predict iron concentration under any given pipe system, water chemistry and hydraulic conditions.
5. Empirical data from pilot-scale study supported the zero-order model form and can be used to quantify the flux term and evaluate flux as a function of the Reynolds Number.
6. Iron flux is constant under laminar flow conditions and, is a linear function of the Reynolds Number under turbulent flow conditions. Flux model coefficients for galvanized iron are different from those for unlined cast iron pipe.

Table 1 Average Flux Experiment Feed Water Quality

	Turbidity	Total Fe	Ca ²⁺	Mg ²⁺	Na ⁺	pH	Alkalinity (mg/L	Conductivity	TDS	Cl ⁻	SO ₄ ²⁻
	(NTU)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		as CaCO ₃)	(μ S/cm)	(mg/L)	(mg/L)	(mg/L)
Feed	0.306	0.045	68	6.4	31	7.96	148	557	377	38	66

Table 2 Unlined Cast Iron Pipe Flux Experiment Data

Flow Rate	Flow Velocity	HRT	Reynolds	Log Reynolds	Δ Turbidity	Δ Iron	Flux, Km
m ³ /min (gpm)	m/s (ft/s)	(Days)	Number	No.	(ntu)	μ g Fe/L	mg/m ² /day (mg/ft ² .day)
0.00008 (0.02)	0.00007 (0.0002)	4.40	10.8	1.03	2.782	381.1	3.30 (0.31)
0.0002 (0.05)	0.00017 (0.0006)	1.76	27.0	1.43	1.128	154.5	3.34 (0.31)
0.0007 (0.18)	0.00066 (0.0022)	0.460	103	2.01	0.260	35.62	2.93 (0.27)
0.0011 (0.29)	0.0010 (0.0033)	0.303	157	2.19	0.058	8.00	1.0 (0.90)
0.0018 (0.48)	0.00163 (0.005)	0.187	254	2.40	0.093	12.71	2.59 (0.24)
0.0028 (0.74)	0.0026 (0.009)	0.117	405	2.61	0.079	10.82	3.51(0.33)
0.0035 (0.92)	0.003 (0.011)	0.095	502	2.70	0.225	30.75	12.38 (1.15)
0.0056 (1.48)	0.0051 (0.017)	0.060	794	2.90	0.143	19.55	12.44 (1.16)
0.0057 (1.51)	0.0052 (0.017)	0.059	810	2.91	0.033	4.52	2.94 (0.27)
0.0081 (2.14)	0.0074 (0.024)	0.041	1161	3.06	0.053	7.29	6.79 (0.63)
0.0088 (2.32)	0.008 (0.026)	0.038	1253	3.10	0.020	2.74	2.75 (0.26)
0.011 (2.91)	0.010 (0.033)	0.030	1566	3.19	0.042	5.72	7.18 (0.67)
0.0117 (3.09)	0.011 (0.035)	0.028	1674	3.22	0.054	7.40	9.93 (0.92)
0.0142 (3.75)	0.013 (0.042)	0.024	2019	3.31	0.016	2.23	3.60 (0.33)
0.0155 (4.1)	0.014 (0.044)	0.021	2213	3.35	0.070	9.59	17.0 (1.6)
0.0235 (6.21)	0.021 (0.070)	0.014	3353	3.53	0.018	2.50	6.72 (0.6)
0.0341 (9.0)	0.031 (0.102)	0.010	4859	3.69	0.079	10.82	42.2 (3.9)
0.0435 (11.5)	0.040 (0.130)	0.0058	8260	3.92	0.057	7.77	51.5 (4.8)
0.0579 (15.3)	0.053 (0.174)	0.0046	10311	4.01	0.082	11.16	92.3 (8.58)
0.0723 (19.1)	0.066 (0.217)	0.0029	16466	4.22	0.082	11.16	147.4 (13.7)
0.1154 (30.5)	0.105 (0.346)	0.0022	21918	4.34	0.082	11.16	196.2 (18.2)
0.1537 (40.6)	0.140 (0.465)	0.0016	29476	4.47	0.089	12.19	288.2 (26.7)

Table 3 Galvanized Iron Pipe Flux Experiment Data

Flow Rate	Flow Velocity	HRT	Reynolds	Log Re	Δ Turbidity	Δ Iron	Flux, K_m
m ³ /min (gpm)	m/s (ft/s)	(days)	Number	No.	(ntu)	(μg/L)	mg/m ² -d (mg/ft ² -d)
0.000012 (0.0032)	0.0000016 (5.4x10 ⁻⁶)	4.49	5.1	0.71	2.802	383.84	1.28 (0.12)
0.00003 (0.008)	0.0000041 (1.4x10 ⁻⁵)	1.78	13.0	1.11	1.568	214.79	1.81 (0.17)
0.00038 (0.1)	0.000052 (1.7x10 ⁻⁴)	0.142	162.1	2.21	0.115	15.73	1.65 (0.15)
0.00087 (0.23)	0.00012 (3.9x10 ⁻⁴)	0.062	372.9	2.57	0.017	2.34	0.56 (0.05)
0.0016 (0.42)	0.00022 (7.1x10 ⁻⁴)	0.034	680.9	2.83	0.021	2.93	1.29 (0.12)
0.003 (0.8)	0.00042 (1.4x10 ⁻³)	0.018	1297.0	3.11	0.026	3.49	2.94 (0.27)
0.0034 (0.9)	0.00047 (1.5x10 ⁻³)	0.0158	1459.1	3.16	0.014	1.92	1.81 (0.17)
0.0038 (1.0)	0.00052 (1.7x10 ⁻³)	0.0142	1621.2	3.21	0.022	3.01	3.17 (0.29)
0.0045 (1.19)	0.00062 (2.0x10 ⁻³)	0.0120	1929.2	3.29	0.055	7.53	9.42 (0.88)
0.0051 (1.34)	0.0007 (2.3x10 ⁻³)	0.0106	2172.4	3.34	0.020	2.71	3.81 (0.35)
0.0065 (1.72)	0.00089 (2.9x10 ⁻³)	0.0083	2793.3	3.45	0.038	5.26	9.52 (0.89)
0.0189 (5.0)	0.0026 (8.5x10 ⁻³)	0.0028	8106.0	3.91	0.043	5.95	31.2 (2.9)
0.034 (8.98)	0.0047 (1.5x10 ⁻²)	0.0016	14558.3	4.16	0.045	6.14	57.9 (5.4)
0.058 (15.3)	0.0079 (2.6x10 ⁻²)	0.0009	24820.5	4.39	0.056	7.70	124 (11.5)

Table 4 Flux models Under Fixed Water Chemistry

Material	Flux, K_m (mg Fe/m ² .day)	
	Laminar Flow	Turbulent Flow
Galvanized Pipe:	1.99	4.5x10 ⁻³ (Re-2000) + 1.99
Unlined Cast Iron:	4.16	9.0x10 ⁻³ (Re-2000) + 4.16

$$(\text{mg/m}^2.\text{day}) \div 10.7639 = \text{mg/ft}^2.\text{day}$$

Figure 1 Change in Iron Concentration with Hydraulic Retention Time

Figure 2 Pilot Research Facility and the Pilot Distribution Systems

Figure 3 Average Effluent Iron Concentration for Single Material PDS Pipes, 5-day HRT

Figure 4 Correlations between Iron and Turbidity

Figure 5 Time Series Response of Turbidity during Flux Experiment

Figure 6 Flux as a Function of Reynolds Number: All Experiments considered

Figure 7 Flux –Log Reynolds Number Plot

Figure 8 Flux (K_m) Behavior for all Laminar and Turbulent Flow Conditions

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