Assessment of Source Water Blends on Distribution System Water Quality

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Abstract

A pilot-scale distribution system was constructed using aged pipe materials obtained from the Tampa Bay Water member governments' distribution systems (PVC, unlined cast iron, lined iron, and galvanized). Pilot-scale treatment facilities were developed to provide finished water representing current and anticipated supplies in the Tampa Bay Water service area. After a three-month period of equilibration, different blends of the finished waters were introduced into the pilot distribution system. Water quality impacts were documented, including elevation of apparent color, iron, and turbidity. This impairment of water quality is believed to result from the release of corrosion products from the interior surface of the unlined cast iron and galvanized pipe materials. Introduction of source waters with the greatest disparity from historic groundwater sources posed the greatest potential for water quality alteration. Source water characteristics that appear to be relevant include alkalinity, chloride, conductivity, and sulfate. Experimentation is continuing with objectives to investigate mitigation measures.

Keywords: blend, iron, color, corrosion, water quality, distribution, potable.

Project Overview

The potable water demand for the Tampa Bay Florida area is currently (fall 2002) satisfied almost exclusively from groundwater sources. In order to meet projected short and long-term requirements, Tampa Bay Water is currently developing alternative sources for the regional water supply, including surface water and desalination (reverse osmosis) facilities. The new facilities are projected to go on-line within the next six months. The regional supply is forecasted to consist of groundwater (62%), surface water (27%), and saline (11%) within a five-year horizon. Development and blending of these alternate water resources, with anticipated differences in finished water characteristics relative to historic groundwater sources, presents potential for alteration of water quality in the distribution system. The current study was initiated in August 2000 to investigate variation in distribution system water quality resulting from introduction of various blends of finished water. Data collection will continue into the summer of 2003. This discussion is based on data collected during the first nine months of operation of pilot treatment and distribution systems at the Tampa Bay Water Cypress Creek Site.

Pilot Treatment Systems

Although different treated waters will be used for water supply, it should be noted that the distinct sources will experience a degree of blending both before and after introduction to the member government distribution systems. It is expected that variation in source water composition will be experienced both in time and location throughout the distribution system. Variation with time will occur as the output from each treatment facility is adjusted to satisfy demand. Variation with location will occur as the member governments augment the regional supply from Tampa Bay Water with their own supplies (principally groundwater). Consequently, the actual water quality experienced in the distribution system would be defined by a blend of several sources. It is emphasized that the study approach, and subsequent data analysis, is based on water chemistry parameters rather than treatment source. Nevertheless, in order to complete the experimental program, a variety of individual finished water sources are required.

Seven pilot treatment facilities have been constructed to supply water for delivery to the pilot distribution systems. Four of the pilot plants represent existing (or in construction) facilities. The present discussion will focus on waters from these four existing sources:

1. Conventional groundwater (G1). Aeration, disinfection (free residual followed by ammonia addition to achieve a combined residual), stabilization.
2. Lime softened groundwater (G2). Lime softening, disinfection (free residual followed by ammonia addition to achieve a combined residual), stabilization.
3. Enhanced surface water treatment (S1). Ferric sulfate coagulation, flocculation, settling, filtration, disinfection by ozonation, biologically activated carbon filtration, chlorination (combined residual), stabilization.
4. Reverse osmosis (RO). Reverse osmosis membrane, inorganics addition for stabilization, aeration, disinfection (free residual followed by ammonia addition to achieve a combined residual), stabilization. Addition of inorganic salts (sea salt) is practiced to match the finished water specifications established for the prototype desalination plant (100 mg/L chloride).

In addition, three other pilot plants are operated, representing potential facilities. Data are also included in the present discussion for pilot distribution systems receiving these sources.

1. Lime softened blend (G3). Treatment of blend of groundwater (G1), surface water (S1), and reverse osmosis permeate (RO). Lime softening, disinfection (free residual followed by ammonia addition to achieve a combined residual), stabilization.

2. Membrane treated blend (G4). Treatment of blend of groundwater (G1), surface water (S1), and reverse osmosis permeate (RO). Nanofiltration treatment, inorganics addition for stabilization, aeration, chlorination (combined residual), stabilization.
3. Integrated membrane system (S2). Treatment of surface water. Ferric sulfate coagulation, flocculation, settling, filtration, nanofiltration treatment, inorganics addition for stabilization, aeration, chlorination (combined residual), stabilization.

Pilot Distribution Systems

In order to reproduce water quality effects that would be encountered in the full-scale distribution system, it was critical to use pipe materials with established interior surface characteristics that were representative of the member governments pipes. Adverse water quality impacts are suspected to result from disruption and release of surface constituents (corrosion products, biofilms, and chemical precipitates). Assembly of the pilot distribution systems was completed with aged pipe materials that had historically received a treated groundwater (G1 or G2). Four different materials were obtained: PVC, lined iron, unlined cast iron, and galvanized iron. In order to minimize variability between samples of a particular pipe material, all pipe that was used to construct the pilot distribution system was obtained from the same location.

Eighteen pilot distribution lines were developed. Fourteen of these lines, referred to as hybrid lines, include all four materials. The four remaining lines are single material lines. Due to limited availability of aged pipe, the nominal length of each line is approximately 100 feet. Pipe diameters are six inches, with the exception of galvanized that is two inches. Different quality waters are input to the distribution system, representing various combinations of the seven different finished waters. The single material lines all receive a blend of the three principal sources: G1, S1, and RO. The feeds are varied seasonally (every three months). Provisions exist to permit independent variation in the source water feed and flow rate to each distribution line. Ports are provided to allow intermediate sampling at internal locations within each pilot line. These intermediate ports can be used to isolate effects of individual materials in the hybrid lines or to asses variable residence times in the single material lines.

The data reviewed in this discussion represents the equilibration period (July 2001 to December 2001), Phase I (December 2001 to March 2002), and Phase II (March 2002 to June 2002). The source waters for these blends are defined in Table 1.

In order to create conditions that would be representative of problem reaches in the distribution system, the pilot units are operated to achieve a five-day hydraulic residence time. Since the total quantity of pipe is limited, the resulting velocities are not representative of a full-scale system (extremely small). In order to mimic the hydraulic conditions in a full-scale system, a weekly purge is imposed with a velocity of 1 ft/sec for a sufficient duration to pass five pipe volumes of water. The velocity was selected to limit any accumulation of films on the pipe interior. The purge velocity is not as large as the velocities ordinarily employed for unidirectional flushing of distribution systems.

Table 1. Blend Composition for Phase I and Phase II

PDS – Material	Phase I Sources (%)	Phase II Sources (%)
01 – Hybrid	G1 (100)	G2 (100)
02 – Hybrid	G2 (100)	G1 (100)
03 – Hybrid	S1 (100)	S2 (100)
04 – Hybrid	G4 (100)	G3 (100)
05 – Hybrid	RO (100)	S1 (100)
06 – Hybrid	G1 (55) S1 (45)	G1 (68) RO (32)
07 – Hybrid	G1 (68) RO (32)	G1 (55) S1 (45)
08 – Hybrid	G1 (23) S1 (45) RO (32)	G1 (60) S2 (30) RO (10)
09 – Hybrid	G1 (60) S2 (30) RO (10)	G1 (23) S1 (45) RO (32)
10 – Hybrid	G2 (50) S1 (50)	G2 (62) S1 (24) RO (14)
11 – Hybrid	G2 (62) S1 (24) RO (14)	G2 (50) S1 (50)
12 – Hybrid	G3 (100)	G4 (100)
13 – Hybrid	S2 (100)	RO (100)
14 – Hybrid	G1 (62) S1 (27) RO (11)	G1 (62) S1 (27) RO (11)
15 – Hybrid	G1 (23) S1 (45) RO (32)	G1 (60) S1 (30) RO (10)
16 – Hybrid	G1 (23) S1 (45) RO (32)	G1 (60) S1 (30) RO (10)
17 – Hybrid	G1 (23) S1 (45) RO (32)	G1 (60) S1 (30) RO (10)
18 – Hybrid	G1 (23) S1 (45) RO (32)	G1 (60) S1 (30) RO (10)

Feed and effluent samples are monitored for a large number of parameters as summarized in Table 2.

Table 2. Pilot Distribution System Monitoring Program

Alkalinity
Aluminum
Bromide
Calcium
Chloride
Chlorine – Free
Chlorine – Total
Color – Apparent
Color – True
Conductivity
Copper
Dissolved Oxygen
Fluoride
HAAs
Iron - Total

Iron – Dissolved
Lead
Magnesium
Manganese
Nitrogen – Ammonia
Nitrogen – Kjeldahl
Nitrogen – Nitrate
Nitrogen – Nitrite
NPDOC
ORP
pH
Phosphate – Total
Phosphate – Ortho
Silica (SiO_2)
Sodium

Sulfate
Temperature
TDS
THMs
Turbidity
UV-254

AOC
BDOC
HPC

Pipe Equilibration

The pipe materials were obtained from the member governments during the spring and summer of 2001. The pipes were maintained in a moist condition after excavation during transport to the field site. Upon arrival at the study site, treated groundwater was provided to maintain the interior films in their original condition. The water supplied during equilibration (G1) was believed to be a close match for the historic water that had been exposed to the pipes. Construction of the pilot lines was completed in July 2001.

The harvesting, transport, and re-assembly of the aged pipes would be expected to impose some disruption of the interior films. It was recognized that a period of equilibration would be required to restore the pipe surface characteristics after construction of the pilot distribution system. Elevated (relative to the treated groundwater feed) levels of apparent color, turbidity, and iron (total) were experienced during the equilibration period. The dynamics were described as a first-order impulse response (1). An equilibration period of three months was required to achieve return of the effluent conditions to values equal to the input (1). Introduction of different source water blends was initiated in December 2001.

During the equilibration period, it was determined that effluent values for apparent color were well correlated with turbidity ($r^2 = 0.976$) and total iron concentrations ($r^2 = 0.934$) (1). Effluent data for the hybrid lines during the first six months of operation are presented in Figures 1 and 2 that confirm this observation. Accordingly, apparent color data has been selected for this discussion to characterize water quality effects associated with disruption of surface films.

Figure 1. Correlation Between Apparent Color and Total Iron for PDS Hybrid Lines

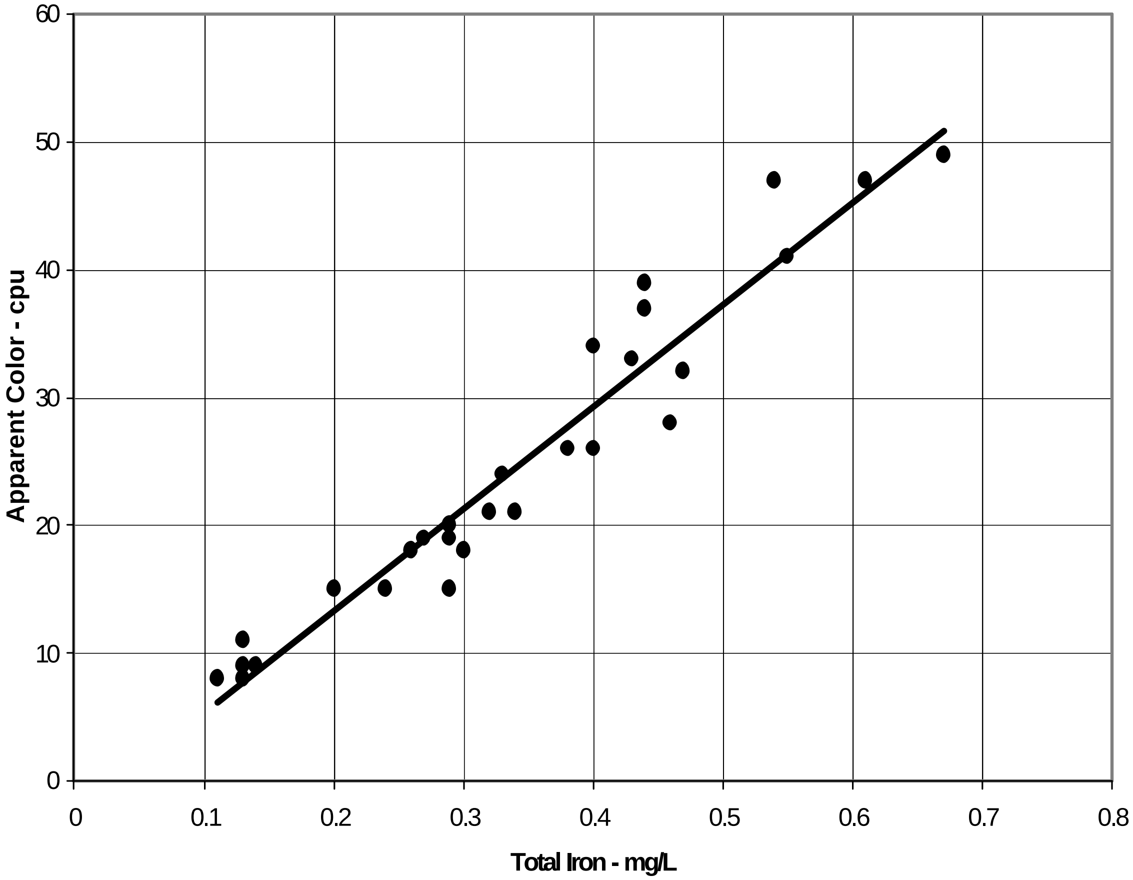
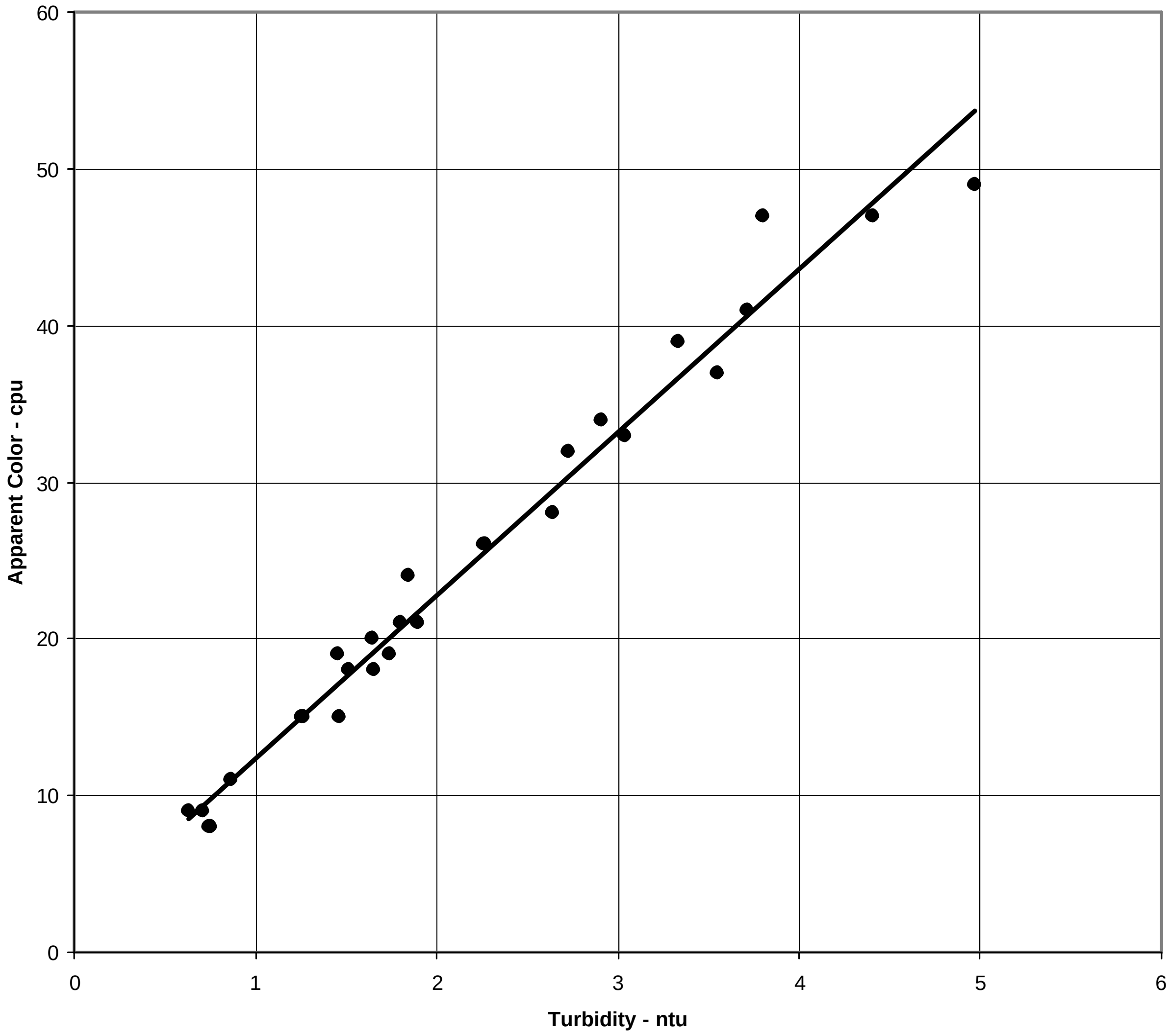


Figure 2. Correlation Between Apparent Color and Turbidity for PDS Hybrid Lines



Response Dynamics

The initial response of the single material cast iron distribution line is discussed to illustrate the dynamics associated with introduction of a new water blend. As reviewed later in this manuscript, the unlined cast iron displayed the largest magnitude response after receipt of a blend of G1, S1, and RO. Relevant data (apparent color) for the first two months are provided in Table 3. It is observed that the response was rapid and persistent. Elevation of effluent values was noted in the first sampling event (elapsed time of five days). Elevated color values have continued throughout the study duration (elapsed time of eight months as of the preparation of this manuscript).

Table 3. Blend Study Initiation, Unlined Cast Iron Line Dynamic Response

Date	Elapsed Time – days	Apparent Color – cpu
07 Dec 01	0	5
12 Dec 01	5	14
27 Dec 01	20	39
03 Jan 02	27	37
10 Jan 02	34	39
17 Jan 02	41	50
25 Jan 02	49	54
31 Jan 02	55	55
07 Feb 02	62	53

Pipe Material Impacts

The effect of pipe material on release of color is characterized by the data in Table 4. Results are provided for two separate phases with a duration of three months each. The single material pipes received the same water blend during each phase, as summarized in Table 4. It is noted that these three sources were selected because they represent the principal sources of the regional water supply.

The results from Table 4 identify the unlined cast iron material as the source of the greatest film disruption. The apparent color increase, based on average values, was determined to be 41 and 29 cpu for Phase I and Phase II, respectively. The effluent from the line indicated an obvious yellow color when viewed in a bucket of comparable water depth to a bathtub or toilet. In contrast, the effluent from the lined iron and PVC materials did not display any significant elevation (Δcolor $\leq$ 1 cpu) relative to the influent. The galvanized material, often thought to be a problem in older distribution systems, demonstrated a moderate release of color with average color increases of 5 and 10 cpu.

Table 4. Pipe Material Impact on Apparent Color Release

Phase	Blend	Apparent Color – cpu			
		Unlined Cast Iron	Lined Iron	PVC	Galvanized
I	G1 (23%) S1 (45%) RO (32%)				
Feed	Average	5	3	3	3
	Range	2 to 10	1 to 5	< 1 to 5	1 to 6
Effluent	Average	46	4	3	8
	Range	5 to 66	< 1 to 15	< 1 to 4	1 to 11
II	G1 (60%) S1 (30%) RO (10%)				
Feed	Average	5	4	4	6
	Range	1 to 9	<1 to 7	< 1 to 10	< 1 to 12
Effluent	Average	34	5	4	16
	Range	26 to 39	2 to 7	< 1 to 7	8 to 31

Feed Water Quality Impacts

Selected results for the hybrid pilot distribution lines are provided in Tables 5 and 6 for Phase I and II, respectively. Data are included in these tables for only four of the hybrid lines representing the four existing (or imminent) treatment facilities: G1, G2, S1, and RO. The total assembly of data from all fourteen hybrid lines was used for examination of dependence of color release on selected key water quality parameters (alkalinity, calcium, chloride, conductivity, pH, and sulfate).

The first observation is the relative absence of any adverse water quality change associated with the G1 water source. This occurrence validates the G1 source as an experimental control, recognizing that the characteristics of G1 are intended to be similar to the historic water that was used to equilibrate the pipes during years of service. A similar conclusion is appropriate for the G2 (lime softened) source. In marked contrast, however, release of corrosion products with an associated increase in apparent color, iron, and turbidity was experienced with the S1 and RO source waters. For the pilot distribution line receiving S1, the average apparent color values increased from 3 to 37 and 4 to 49 cpu in Phase I and II, respectively. The corresponding increase for the RO distribution line was 2 to 24 cpu and 1 to 47 cpu for Phase I and Phase II, respectively.

Table 5. Distribution System Water Quality Impacts – Phase I

Parameter	G1	G2	S1	RO
PDS Feed				
Apparent Color – cpu	4	3	3	2
True Color – cpu	3	3	2	2
Total Iron – mg/L	0.05	0.01	0.01	0.01
Dissolved Iron – mg/L	0.02	0.01	0.01	0.01
PDS Effluent				
Apparent Color – cpu	8	9	37	24
True Color – cpu	3	3	1	1
Total Iron – mg/L	0.11	0.14	0.44	0.33
Dissolved Iron – mg/L	0.02	0.02	0.03	0.01
Turbidity – ntu	0.75	0.63	3.55	1.84
Alkalinity – mg/L as CaCO3	210	89	68	82
Calcium – mg/L	86.1	37.9	82.8	24.9
Chloride – mg/L	28.8	23.8	48.0	99.5
Conductivity – umho/cm	517	307	532	392
pH	8.02	8.24	8.00	8.32
Sulfate – mg/L	29.0	27.1	245.2	7.3

Table 6. Distribution System Water Quality Impacts – Phase II

Parameter	G1	G2	S1	RO
PDS Feed				
Apparent Color – cpu	4	2	4	1
True Color – cpu	2	2	1	1
Total Iron – mg/L	0.05	0.01	0.01	0.01
Dissolved Iron – mg/L	0.01	0.01	0.01	0.01
PDS Effluent				
Apparent Color – cpu	9	11	49	47
True Color – cpu	2	2	1	1
Total Iron – mg/L	0.13	0.13	0.67	0.54
Dissolved Iron – mg/L	0.01	0.02	0.03	0.02
Turbidity – ntu	0.71	0.86	4.97	3.80
Alkalinity – mg/L as CaCO3	210	95	55	68
Calcium – mg/L	87.9	35.8	69.1	29.2
Chloride – mg/L	29.0	31.9	42.8	92.5
Conductivity – umho/cm	565	359	666	443
pH	7.93	8.07	7.96	8.18
Sulfate – mg/L	26.0	25.8	220.2	5.4

Examination of the effluent data from Tables 5 and 6 indicates that the primary occurrence of color (or iron) is attributable to particulate forms. The dominant form of both color and iron is particulate. The excellent correlation between apparent color and turbidity reported previously corroborates these results. There is no observed increase in true color and very minor increases in dissolved iron concentration ($\leq$ 0.02 mg/L) in spite of significant increases in apparent color and total iron in the distribution lines receiving S1 or RO. This observation suggests a mechanism of film disruption and release of particulate corrosion products.

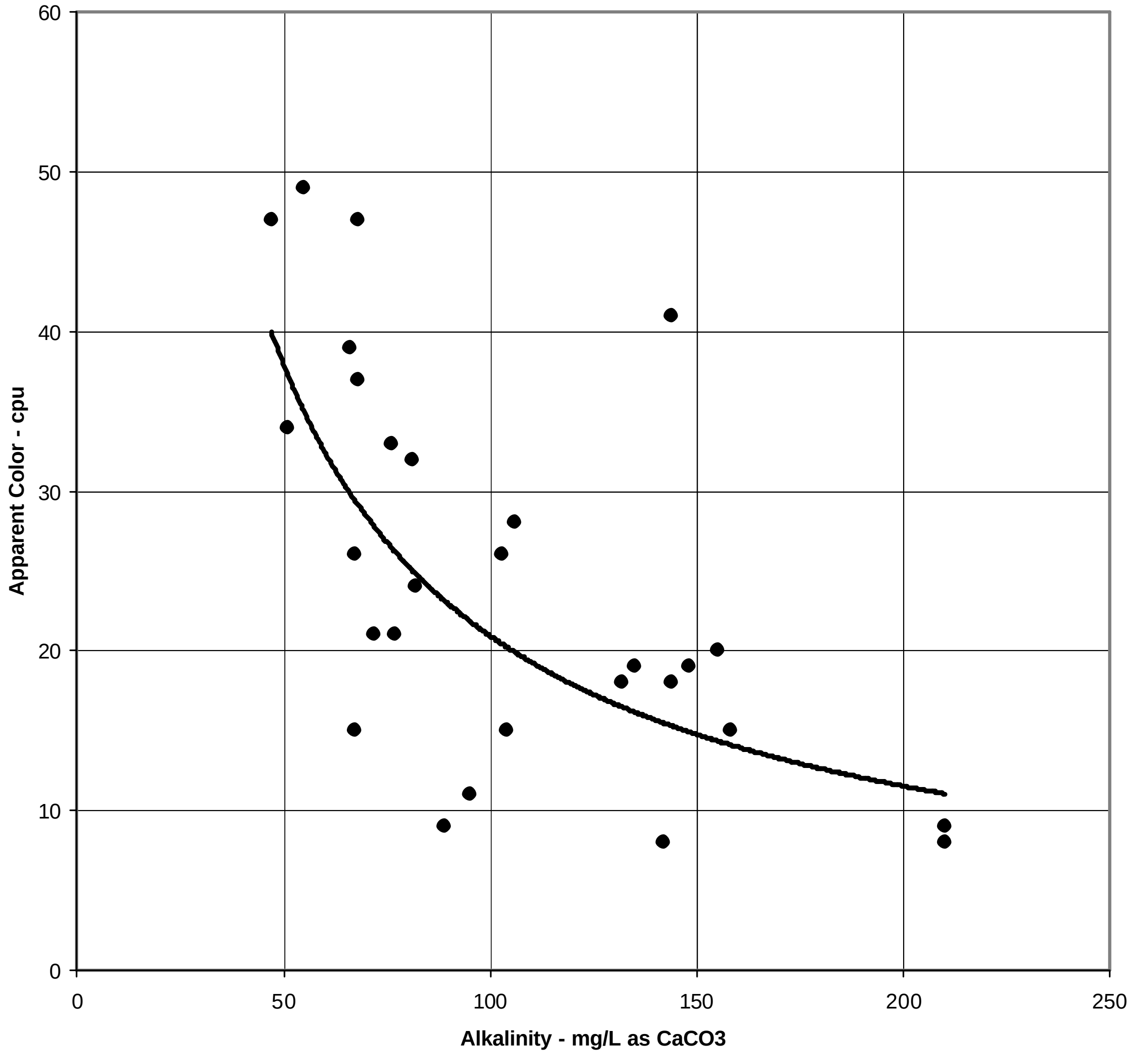
The water quality parameters that are reported in Tables 5 and 6 were selected in the expectation that there would be a potential relation to release of corrosion products from the pipe surface. Alkalinity, calcium, and pH influence the solubility of calcium carbonate. Precipitation of calcium carbonate may protect pipe surfaces from aggressive waters. Conversely, dissolution of a protective deposit of calcium carbonate could result in exposure and subsequent release of corrosion products. According to this mechanism, decreases in pH, alkalinity, or calcium would be expected to accelerate the release of corrosion products from the pipe surface. The elevated presence of the other water quality parameters (chloride, conductivity, and sulfate) would be expected to promote greater corrosion rates.

Data for Phase I and II for all hybrid distribution lines is displayed in Figures 3 to 8 to illustrate the relation between distribution system water quality (apparent color) and the previously cited variables (alkalinity, calcium, chloride, conductivity, pH, and sulfate).

Results that are presented in a two-dimensional format (Figures 3 to 8) for a system with multiple relevant variables must be examined with caution. The data presented represent a portion of the full data that will be collected over a twelve-month cycle to assess seasonal effects. The data base, as presently available, includes confounding effects between factors that may be relevant to release of corrosion products. Specifically, the water source(s) with the highest alkalinity (G1 and blends enriched in G1) also contain the lowest chlorides. The water source(s) with the greatest conductivity (S1 and blends enriched in S1), exhibit low alkalinity. Similarly, the water source(s) with the highest chlorides (RO and blends enriched in RO), also report low alkalinity. It is expected that collection of data through the traditional rainy season in Florida (June to September representing Phase III) will permit development of a data source for S1 with reduced mineral content. Development of the full matrix of data for a twelve-month period is necessary to properly evaluate these interactions.

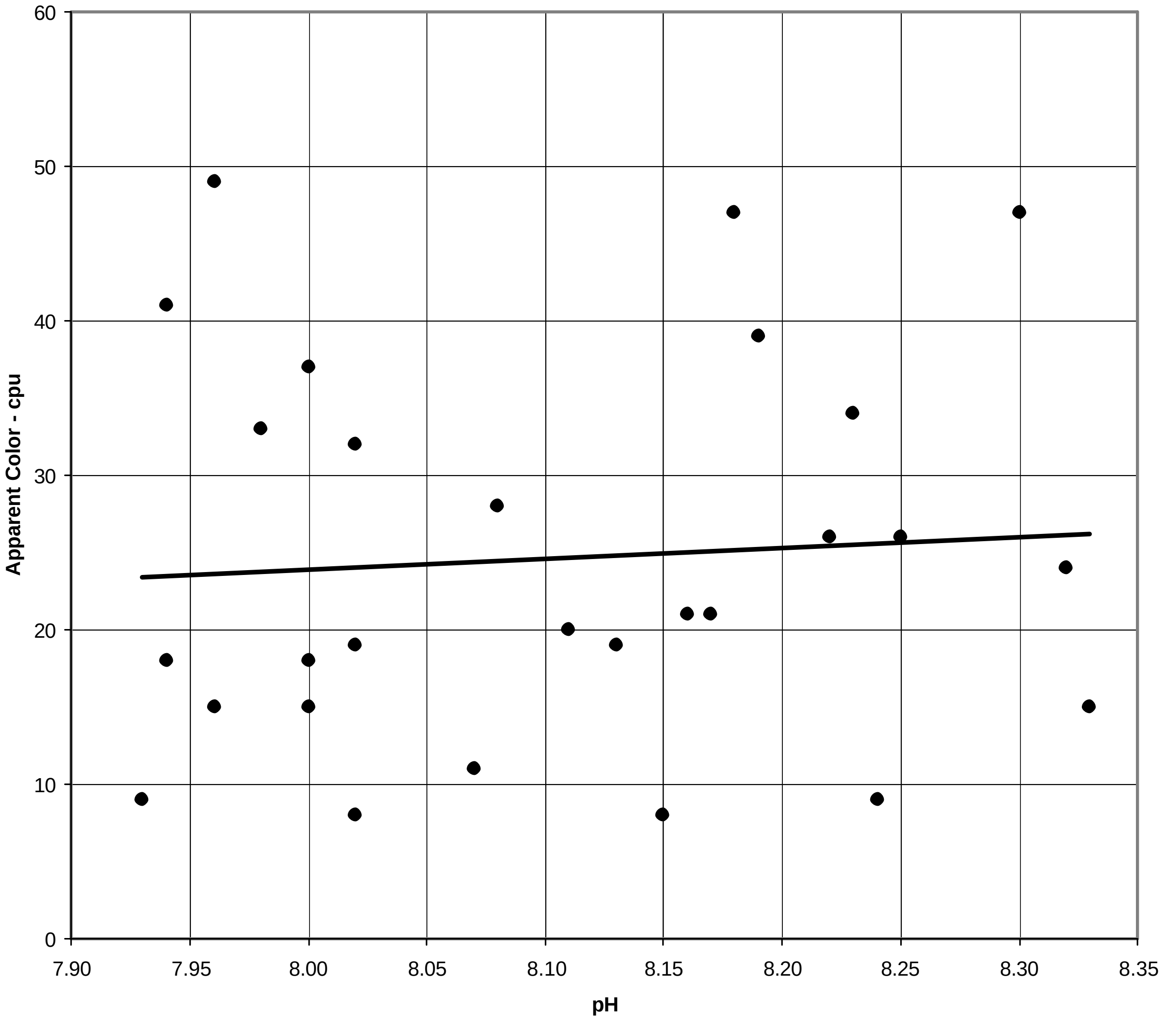
The hybrid system average values for effluent alkalinity and apparent color are reviewed in Figure 3. The results indicate that, for this data set, elevated alkalinity concentrations are associated with reduced release of corrosion products. This observation is consistent with control of release of corrosion products by a carbonate precipitate. It is cautioned that this association may not imply a cause and effect.

Figure 3. PDS Hybrid Lines Effluent Apparent Color as a Function of Alkalinity



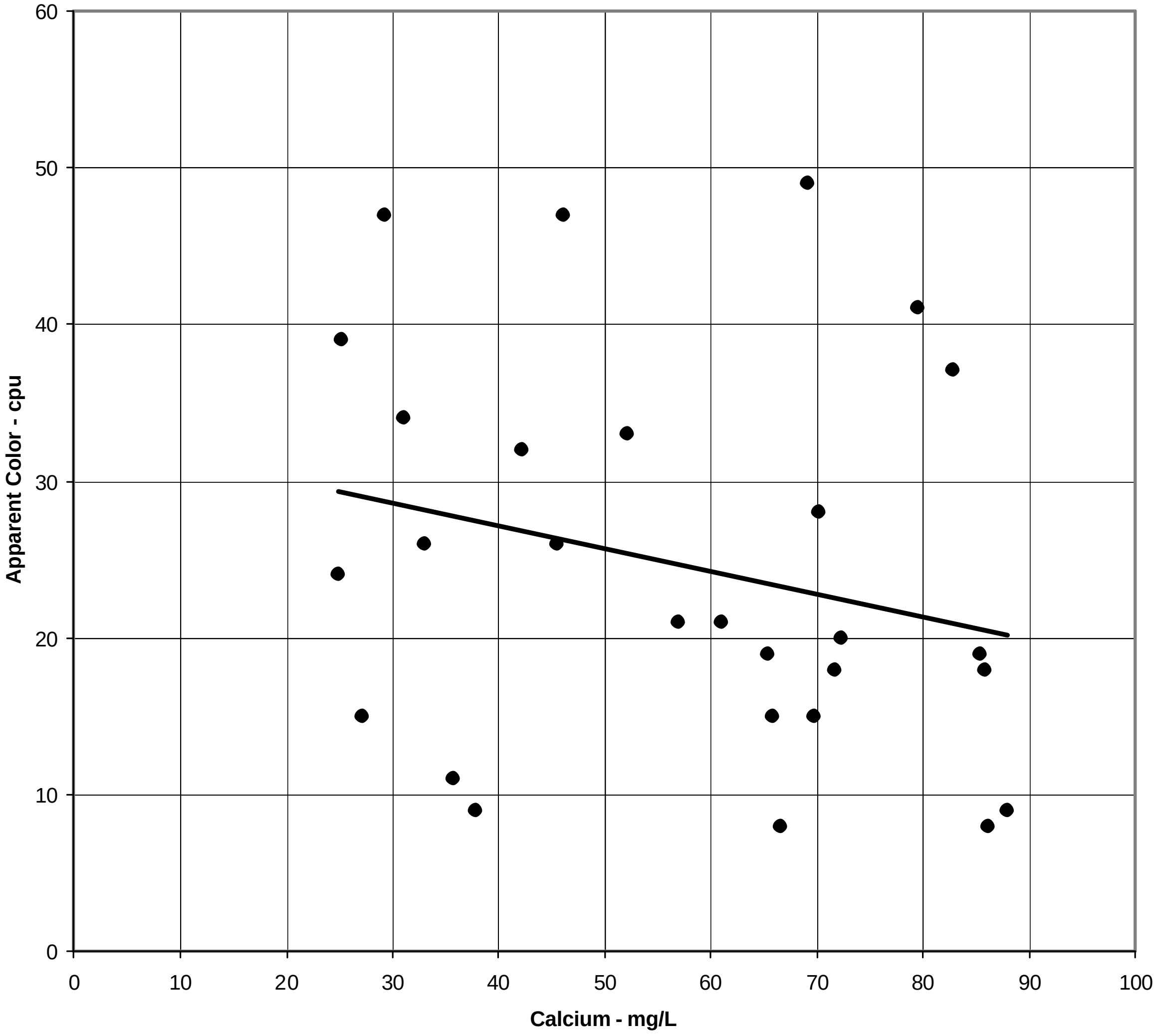
The impact of pH is examined in Figure 4. The particular data set does not include extreme pH values, so that any real relation could be masked by the absence of significant variability in pH (7.93 to 8.33). It is not possible to conclude whether pH is significant for this data set.

Figure 4. PDS Hybrid Lines Effluent Apparent Color as a Function of pH



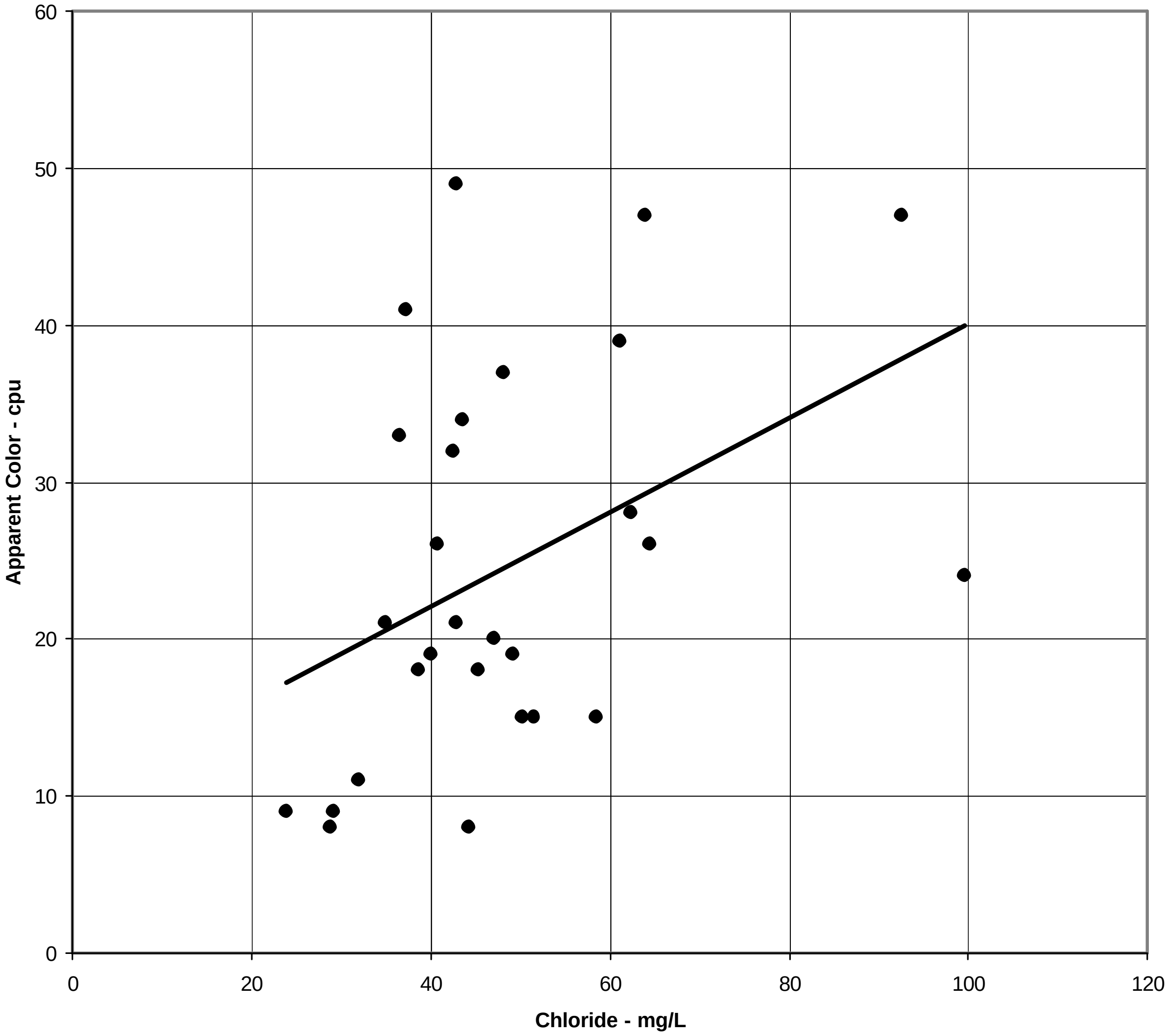
The relation between hybrid system average values for effluent calcium and apparent color is illustrated in Figure 5. It is difficult to identify any clear relation between these two variables based on this data. In contrast, if a calcium carbonate film were present and acted to control the release of corrosion products, a negative correlation would be expected between effluent color and calcium concentration.

Figure 5. PDS Hybrid Lines Effluent Apparent Color as a Function of Calcium



The hybrid system average values for effluent apparent color and chloride are displayed in Figure 6. The results indicate that, for this data set, elevated chloride concentrations are associated with increased color release. It is cautioned that this association may not imply a cause and effect. As noted previously, the sources that contain elevated chlorides also exhibit a depressed alkalinity. In addition, the sources that contain elevated alkalinity also exhibit a depressed chloride.

Figure 6. PDS Hybrid Lines Effluent Apparent Color as a Function of Chloride



The relations between apparent color and conductivity (Figure 7) and sulfate (Figure 8) are qualitatively similar to that noted for chloride. Involvement of specific ions (for example chloride, sodium, or sulfate) would be expected to promote corrosion to the extent that conductivity is relevant. The ions could also express an effect that is not directly related to the conductivity.

Figure 7. PDS Hybrid Lines Effluent Apparent Color as a Function of Conductivity

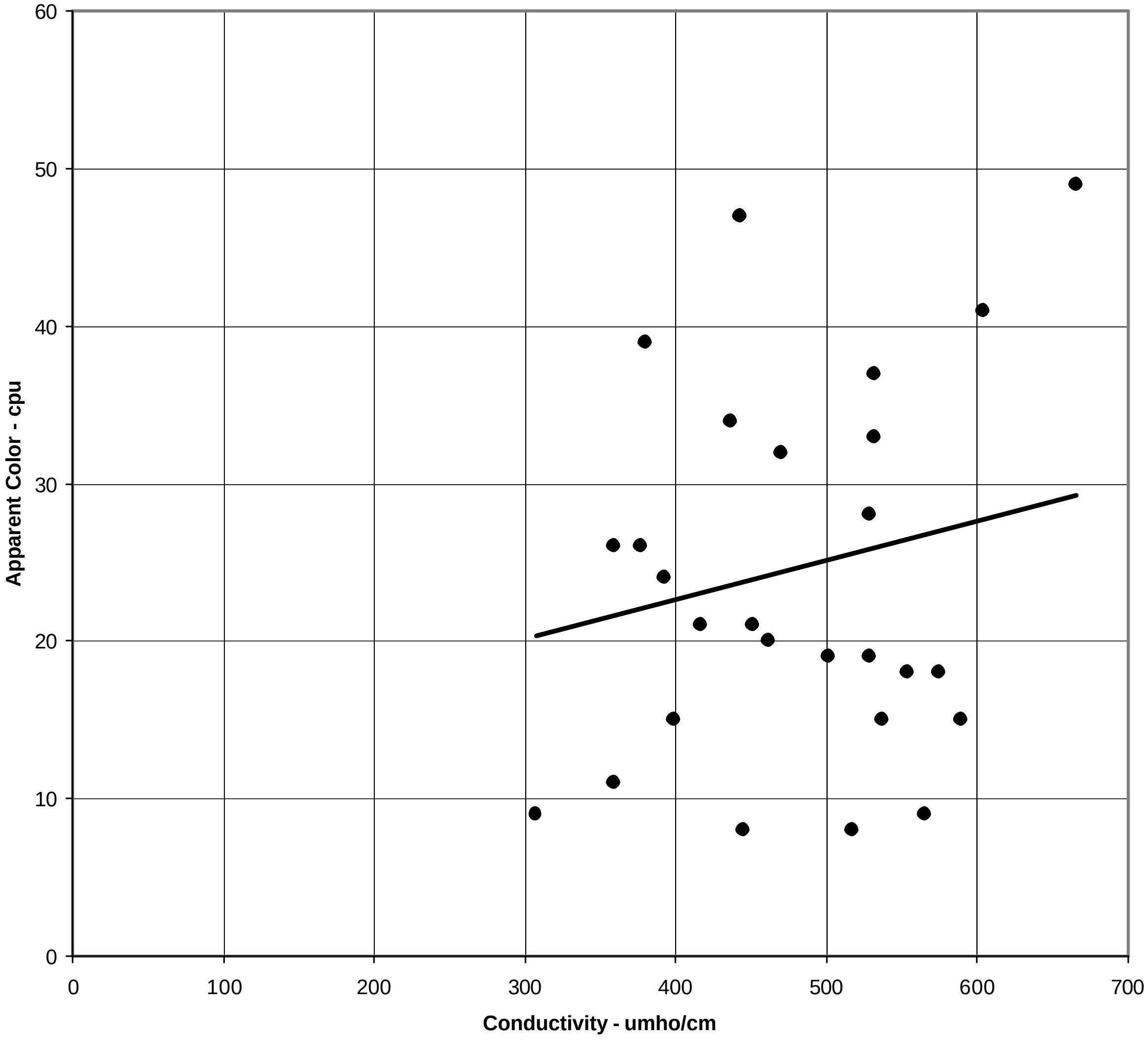
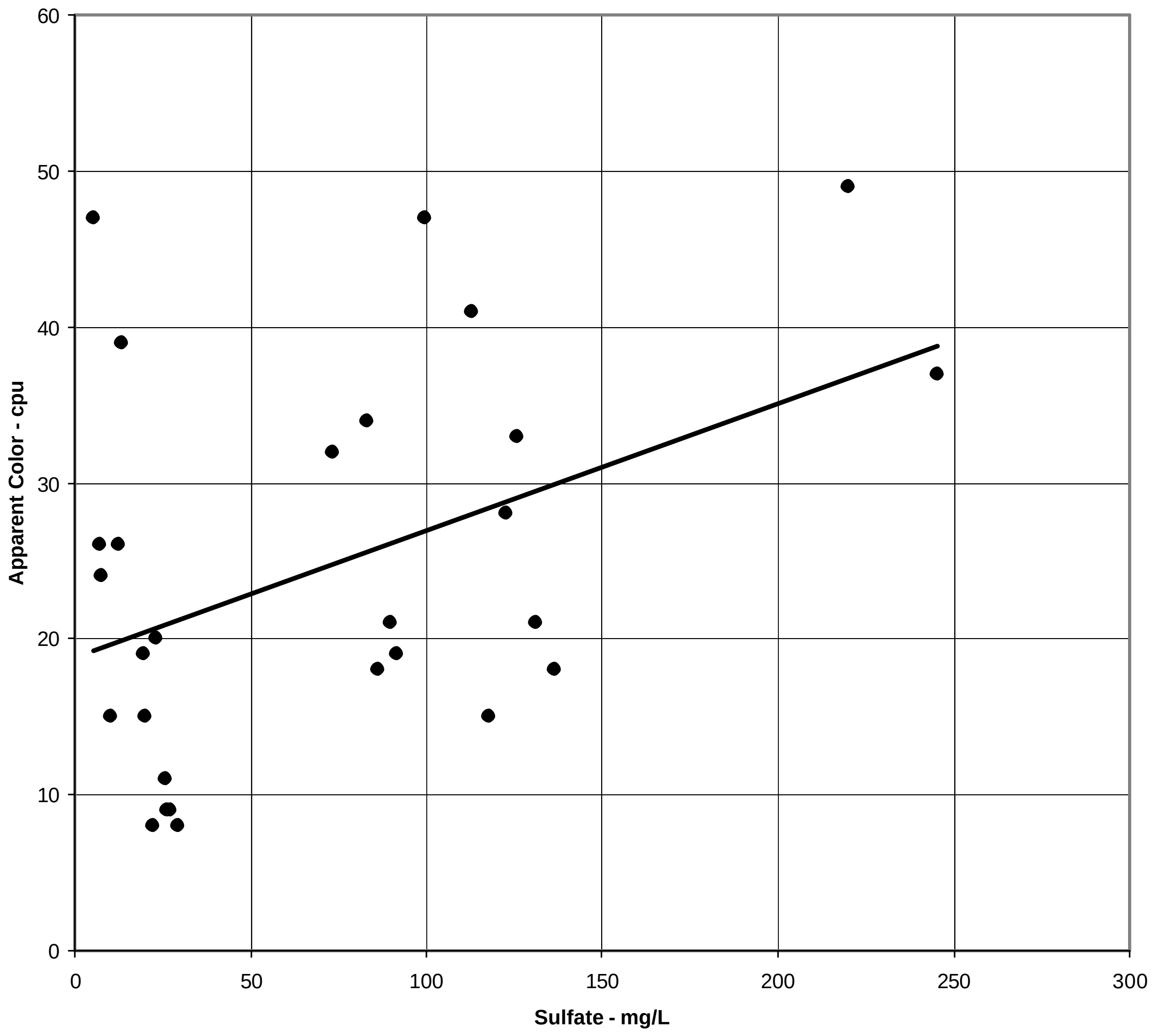


Figure 8. PDS Hybrid Lines Apparent Color as a Function of Sulfate



Conclusions

An experimental distribution system was constructed of aged PVC, cast iron, lined iron, and galvanized pipe materials. All pipes had been in service for many years for delivery of treated groundwater characterized by an elevated alkalinity with modest levels of chloride and sulfate. In an attempt to replicate conditions anticipated when two new regional water treatment facilities (surface water and reverse osmosis desalination) are placed in service to supplement existing groundwater supplies, various blends of product waters were introduced into the pilot distribution system. The distribution system was operated at an extended hydraulic residence time of five days to mimic severe distribution conditions.

1. Impairment of distribution system water quality was experienced in certain cases, as indicated by an increase in apparent color, total iron, and turbidity. Resultant values of these parameters reached unacceptable levels based on generally accepted standards. Maximum values (Phase I or Phase II average) for the hybrid lines were: apparent color, 49 cpu; total iron, 0.67 mg/L; and turbidity, 4.97 ntu.

2. The pipe material was an important determinant of water quality impacts. Unlined cast iron, and to a lesser degree galvanized iron pipe, experienced release of corrosion products. By comparison, PVC and lined iron pipe did not contribute to a degradation of water quality.

3. The source water characteristics were also an important determinant of water quality. Application of a water (G1 or G2) with similar characteristics to the historic water source for the pipe materials did not result in pronounced water quality changes. These waters are characterized by elevated alkalinity, depressed chloride, and depressed sulfate.

4. Introduction of source waters with characteristics that varied significantly from the historic water source resulted in significant increases in apparent color, iron, and turbidity. For this study, the departures from the historic water quality included reduced alkalinity (S1, RO, and blends of S1 and RO), increased chloride (S1, RO, and blends of S1 and RO), and increased sulfate (S1 and blends of S1).

5. The response to the source water change was rapid and persistent. Increases in apparent color were documented within days of the blend change. Elevated color values have persisted to the time of preparation of this manuscript (eight months).

6. The principal form of iron (and color) is particulate. It is hypothesized that disruption of the pipe surface film resulted in the release of corrosion products.

Recommendations

Several findings have been reported that would be of interest for conduct of similar studies.

1. An extended equilibration period was required to reestablish surface characteristics that were disturbed during excavation, transportation, and assembly of pipe materials. The data indicate that stable water conditions were obtained after three months of equilibration with a treated groundwater that was similar to the historic groundwater source of the pipe materials.

2. The water quality impacts could be assessed by measurement of apparent color, total iron, or turbidity. As a matter of convenience, measurement of apparent color has many advantages for field quantification of this water quality impact.

Future Investigation

Operation of the pilot distribution systems will be continued with similar blend scenarios through December 2002 in order to evaluate seasonal water quality variations associated with the surface water source. The project period extends through the summer of 2003, providing an opportunity to investigate measures for mitigation of the color release. Definition of candidate measures is under review at this time.

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