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Flint Water Crisis: What Happened and Why?

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THE FLINT RIVER IS A VARIABLE WATER SOURCE AND THUS A CHALLENGE TO TREAT; OVERSIGHTS AND MISSTEPS COMBINED WITH INHERENT CHEMICAL CONDITIONS SET THE STAGE FOR THE HISTORIC WATER CRISIS IN FLINT, MICH.

There has been much in the news about the water crisis that began in 2014 in Flint, Mich., and the length of time it took for government officials to react. The elevated levels of lead found in the drinking water of residences in Flint have had a profound effect on the level of trust within the community and the state, the economy of the region, and the health and well-being of the residents of Flint and the surrounding communities. As Eric P. Rothstein so aptly stated, “Flint matters because the water utility industry can do better. The crisis, tragic in so many respects, also presents an opportunity for lasting benefit-benefit from recognizing that we are Flint” (Rothstein 2016). We have investigated the chemistry and engineering behind what happened to Flint’s water, why it was corrosive, and the extent to which the system appears to be recovering. This analysis is based on an extensive review of the monthly operating reports (MORs) and other reported documents from the water treatment facilities, and from personal communications with plant operators and managers.

HISTORICAL PERSPECTIVE

The first water distribution system in Flint was privately owned and incorporated as the Flint Water Works Company in 1883 (Dunbar & May 1995). On July 8, 1897, the City of Flint passed an ordinance requiring lead pipes: “all connections with any water mains shall be made with lead pipe” (Anon. 1897).

The City of Flint purchased the Flint Water Company in 1912. By 1930, Flint River water was being treated using alum coagulation before sand filtration, with the plant rated at 28

mgd (Hardin 1932). Construction on a new treatment plant for the City of Flint began in 1952 and was completed in 1954. At that point, treatment of the Flint River included prechlorination, coagulation with alum, lime-soda ash softening, recarbonation, filtration, the addition of polyphosphate for corrosion control, and postchlorination. Taste-and-odor-causing compounds were removed using activated carbon, along with the addition of ammonia and sodium chlorite. The plant was rated at a capacity of 59 mgd, with a maximum overload capacity of 86 mgd. The 50th percentile pH, color, and turbidity of the finished (tap) water were 10.3, 2, and 0.1 ppm (silica scale; approximately equivalent to 0.02 Jtu), respectively. The total and noncarbonate hardness were 86 and 49 mg/L as CaCO₃ (calcium carbonate), respectively (Wiitala 1963).

In 1967, Flint began purchasing wholesale treated water from the Detroit Water and Sewage Department (DWSD). While the water quality of the Flint River was poor as a result of unregulated discharges by industries and municipalities (Leonardi & Gruhn 2001), the principal reason for the switch was to ensure a sufficient quantity of water for the growing population (Carmody 2016). After 1967, the Flint Water Service Center (FWSC) was maintained as a backup water treatment facility, treating Flint River water two to four times a year for periods of only a few days. The National Pollutant Discharge Elimination System permit allows the treated water to be discharged back into the Flint River. In 2012, the Board of Water Commissioners for the City of Detroit approved a resolution that would allow the DWSD director to enter into contractual arrangement to allow blending of treated Flint River water with that purchased from DWSD as a cost-saving measure (City of Detroit 2012). While DWSD and the City of Flint never entered into a contractual agreement, it is unclear whether blending of these two different waters actually occurred.

With the goal of reducing the costs for treated water (Felton 2016), Flint officials decided in 2013 to join the newly formed Karegnondi Water Authority (KWA), which was constructing its own pipeline to transmit raw water from Lake Huron. In the interim, the City of Flint had the option to continue to purchase treated water from DWSD (whose source was Lake Huron) or treat Flint River water at its own facility. After failing to come to an agreement on a short-term contract with DWSD, Flint decided to use water from the Flint River and treat it at the FWSC.

Many warnings and concerns were voiced regarding the use of the Flint River as a community water source. For example, Brian Larkin, then associate director of the (Michigan) Governor's Office of Urban and Metropolitan Initiatives, foretold the crisis in a Mar. 14, 2014, e-mail message to several others in the governor's office: "The expedited time-frame is less than ideal and could lead to some big potential disasters down the road." Mike Glasgow, laboratory and water quality supervisor at the plant, warned in an Apr. 25, 2014, e-mail to the State of Michigan Department of Environmental Quality (MDEQ), "I do not anticipate giving the OK to begin sending water out anytime soon. If water is distributed from this plant in the next couple weeks, it will be against my direction." Despite concerns, the FWSC switched from purchasing and distributing water from DWSD to treating water at its facility in Flint. In doing this, the source water changed from Lake Huron to the Flint River.

Within a few weeks of the switch, residents started complaining about the color, taste, and odor of their drinking water. In May 2014, they informed officials that the water was causing rashes, especially in children (MDEQ e-mail records). During this time, red water and discoloration were observed throughout the distribution system (Veolia North America 2015, Felton 2014), and there was an unusually large number of water main breaks (Fonger 2015). General Motors Corporation complained about the corrosiveness of the water on its engine parts and in October 2014 switched to using water from Flint Township instead of from Flint.

Starting in summer 2014, a number of violations occurred. *Escherichia coli* (*E. coli*) and total coliform violations resulted in the issuance of three boil-water alerts within a 22-day period during summer 2014 (Emery 2016; Fonger 2014a, 2014b). As shown in Table 1, total trihalomethane (TTHM) concentrations at several sampling locations exceeded the 80 µg/L regulatory limit during May and August 2014 (Lockwood, Andrews, & Newman 2015). As a result, the MDEQ requested a preemptive operational evaluation in September 2014 and notified Flint of an initial quarterly violation of the Safe Drinking Water Act (SDWA) Disinfection/Disinfection Byproducts (D/DBP) Rule in December 2014 (Flint Water Advisory Task Force 2016; Table 1).

In February 2015, the City of Flint sampled Flint resident Lee Ann Walters' home and found lead in her water at a concentration of 104 µg/L (e-mail correspondence between US Environmental Protection Agency [USEPA] Region 5 and MDEQ dated Feb. 26, 2015; Flint Water Advisory Task Force 2016). By Aug. 31, 2015, Marc Edwards, a professor at Virginia Polytechnic Institute and State University, had analyzed 120 samples from Flint homes. He found that 20% of the samples had lead levels that exceeded the 15 µg/L action level and that the 90th percentile was 30 µg/L (Roy 2015a). In September, a team led by a local pediatrician, Mona Hanna-Attisha, published data showing that blood lead levels (BLLs) in children increased significantly after the switch to the Flint River as a water source (Hanna-Attisha et al. 2016; Kennedy et al. 2016). In the area of Flint that had the highest lead levels in the water; the BLLs in children who were tested increased by a factor of about 2.5.

The city was required by the SDWA Lead and Copper Rule to conduct sampling for lead and copper in Tier 1 premise plumbing over six-month periods. Although not all of the homes sampled were Tier 1 sites (City of Flint 2016), the first round of sampling revealed that the 90th percentile lead concentration was greater than that observed during the previous five rounds of testing (Figure 1); by the end of the second six-month sampling period, the 90th percentile lead level was almost three times greater than that observed in the previous 15 years (Figure 1).

After much publicity regarding the lead problem, on Oct. 16, 2015, the source water for the City of Flint was switched back to treated Lake Huron water supplied by DWSD, with approximately 1 mg/L phosphorus to inhibit corrosion. Because the lead levels measured in the water remained high in some houses, on Dec. 9, 2015, the concentration of the phosphate corrosion inhibitor was increased by adding an additional ~2.5 mg/L phosphoric acid (P) at the FWSC.

Finally, in February 2016, information on the increase in the number of cases of Legionellosis that occurred in Flint in the summers of 2014 and 2015 was released. Ninety-one cases and 12 deaths have been confirmed in the Flint area, up from six to 13 cases a year before the switch to Flint River water (Anderson 2016). The source of the outbreak has not been definitively determined or directly connected to the Flint water system, but as noted by Anderson (2016), the illnesses began after Flint changed its water supply. Given the low residual disinfectant levels (chlorine in this case) and the presence of iron in the water in the distribution system (Veolia North America 2015, Felton 2014), along with high concentrations of assimilable organic carbon that would have likely formed during the ozonation of the high total organic carbon (TOC) Flint River water, conditions could have been conducive to biological growth and the propagation of *Legionella* in the distribution network.

WATER TREATMENT AT THE FLINT WATER TREATMENT PLANT

During the period from April 2014 to October 2015, the turbidity of the raw Flint River water at the FWSC plant ranged from 1.5 to 45.2 ntu (according to the MORs). The chloride level in the raw water ranged from 38 to 82 mg/L, with the monthly average values ranging from 38 to 54 mg/L. The TOC of the Flint River was reported to be 10.3 mg/L on May 22, 2014 (Lockwood, Andrews, & Newman 2014). The FWSC raw water intake is upstream of most development in Flint, but there is still some concern about industrial contaminants and sewage (Fonger 2014c).

Although numerous changes were made to the treatment process over the course of the 1.5 years of treatment, as of November 2014, when the draft Operational Evaluation Report (OER) was published, the treatment train was as shown in Figure 2 (Lockwood, Andrews, & Newman 2014). Water was drawn from the Flint River through raw water screens, then pumped into the ozonation basin. Sodium bisulfate was added in the last cell of the ozone contactor to destroy any residual ozone left in the water. The water then flowed into a rapid mix tank, where ferric chloride was added. From there, the water entered a three-stage flocculation unit followed by plate settlers. From the settling unit, water flowed into an upflow clarifier, where lime and anionic and cationic polymers were added. Fluoride was added at the outlet of the clarifier. From there, water moved into the recarbonation unit, where carbon dioxide was added to lower the pH. Chlorine was added just before dual media (sand/anthracite) filtration and again before flowing into a 3-mil-gal clearwell (Figure 2).

Before the switch to Flint River water, Laboratory and Water Quality Supervisor Mike Glasgow sent MD EQ staff engineers an e-mail message on Apr. 17, 2014, stating, "I do not anticipate giving the OK to begin sending out water anytime soon." While the message sounded the alarm that staffing and monitoring plans were inadequate, it has not been reported how poorly equipped the plant was. It is clear from the MOR that the plant was woefully unprepared for full-time operation on Apr. 25, 2014. The May 2014 MOR reveals that the plant had only four to five days of polymer available to "use as a trial on two different occasions." Supervisory control and data acquisition (SCADA) upgrades were incomplete and out for bid. Filter headloss meters were not operational on the SCADA system. Also, chlorine residual monitoring equipment at the point of entry into the

distribution system had not been installed, so chlorine levels would have had to have been measured by taking grab samples from the clearwell as well as from a tap in the laboratory. It appears that, on the basis of the MORs, chlorination after filtration was not used until May 17, 2014. Fluoridation was not implemented until July 2, 2014. The water utility did not have a corrosion-control plan, and it had not installed corrosion control equipment when the water was switched back to DWSD on Oct. 16, 2015. On the basis of the comments in the MORs, the filter headloss meters were never made operational.

Figures 3 and 4 illustrate the variability in the chemical dosages that were used during the treatment process. Bench-scale jar testing for trihalomethane (THM) removal was not completed until sometime between January and August 2015 (City of Flint 2015). Without any treatability studies on which to determine chemical dosages until late August 2015 (City of Flint 2015), it appears that plant personnel were left to attempt to address the plethora of complex water quality issues and complaints by trial and error. Significant changes were made to chemical dosages, and the reasons for these changes were often not apparent. For example, the dosage of the anionic polymer (P-142PWG) added to the lime softening process to enhance settling was initially 0.05 mg/L; the anionic polymer dosage was later increased significantly, with concentrations approaching or exceeding the maximum dosage of 1.0 mg/L as recommended by NSF International (2016). The OER issued in August 2015 (Lockwood, Andrews, & Newman 2015) states that “feeding coagulation/flocculation polymer aids” do not have “a meaningful benefit.” However, while there was a slight decrease in polymer use in March 2015, both anionic and cationic polymers were used continuously until the plant was shut down in October 2015. The reasons for the increase in the lime dosage in November 2014 and then the decrease in February and March 2015 are unknown.

It is unclear what ozone dosage was used over the majority of the treatment period because it was not recorded in the MORs until March 2015. The OER (Lockwood, Andrews, & Newman 2015) states that the ozone system was not feeding optimally until “corrective modifications” were made in January 2015. The corrective modifications appear to have been “repairs to gauges and programming” to produce “proper ozone under manual operation.” Repairs were planned for the first quarter of 2015 to “allow automatic operation,” but it is unclear if those were made.

Bromate is a disinfection by-product formed by the reaction of bromide ion with ozone. Monthly bromate monitoring for the first year of operation was required by the D/DBP Rule and were ordered by MDEQ staff on Sept. 11, 2014. The first bromate sample was to be taken by the end of that month. The 2014 consumer confidence report (City of Flint 2014) states that the bromate levels varied from 0 to 23 µg/L, and that no violation occurred. However, as the reporting limit for bromate was 5 µg/L (Stark 2016), the bromate levels actually varied between <5 and 23 µg/L.

The maximum contaminant level (MCL) for bromate is 10 µg/L, as a running annual average (RAA), determined at the point of entry. No data for bromate concentrations are provided in the 2015 consumer confidence report (City of Flint 2016); however, e-mail correspondence on Apr. 6, 2015, between MDEQ staff members indicate that the RAA was “hovering just

above the MCL of 10 ppb.” E-mail correspondence between FWSC staff and MD EQ staff indicates that bromate results were not reported for five of the 13 months after September 2014, even though ozone was used continuously at the plant.

Disinfection was accomplished using gaseous chlorine which, as shown in Figure 2, was to be added both before and after filtration. The total chlorine dosage varied from ~5 mg/L in the winter months to > 7 mg/L in the summer months (Figure 5). Not surprisingly, the chlorine demand, calculated by subtracting the chlorine residual leaving the treatment plant from the applied chlorine dosage, increased during the summer and decreased during the winter. The location of chlorine application varied significantly during the treatment period, with no post-filtration chlorination until May 17, 2015, and then no prefilter chlorination after Aug. 3, 2015. No justification for these changes was documented in the MORs. The softening bypass stream had been reduced to no greater than 20% in November 2014 in an attempt to reduce chlorine demand. The minutes of the Nov. 7, 2014, TTHM Response Planning Meeting (MDEQ e-mail correspondence) state that the bypass was discontinued “and it appears that the chlorine demand has dropped by 0.5–1.0 mg/L.” However, as shown in Figure 5, this drop appears to be a part of a downward trend that occurred before this change. In summer 2015, the chlorine demand was somewhat lower than in summer 2014, but it is not clear whether this is due to eliminating the softening bypass stream or to other causes.

Difficulties were encountered in maintaining chlorine residuals throughout the distribution system throughout the 1.5 years of treatment and continues to be problematic, even after the change back to DWSD water. As shown in Figure 6, chlorine residuals in the treated Flint River water were low during the first few months of operation. In response to this and the detection of *E. coli*, the post-filtration chlorine dosages were increased from 0.0 to 2.9 mg/L in June 2014 and then to ~3.8 mg/L in July–October 2014, resulting in a decrease in the number of distribution system samples with no detectable chlorine residual. However, as shown in Table 1, increasing the chlorine dose resulted in increased concentrations of TTHMs. Although the FWSC reported increases in chlorine residuals after Oct. 2014, Marc Edwards reported that in August 2015, 41 % of the samples his group collected had no detectable chlorine (Roy 2015b). This team’s sampling and analysis in late October 2015 revealed that 16 of the 30 samples collected had chlorine residuals less than 0.2 mg/L and 10 had chlorine levels less than 0.1 mg/L. The US Environmental Protection Agency (USEPA) Safe Drinking Water Task Force remains concerned about chlorine residual levels in Flint’s water (Emery 2016).

The 24-month source water sampling for *Cryptosporidium*, *E. coli*, and turbidity to determine bin placement required by the SDWA Long-Term 2 Enhanced Surface Water Treatment Rule was not done before the switch to Flint River water, apparently because MDEQ staff believed the Flint River was only a temporary source (MDEQ e-mail conversations), despite the fact that construction on the 80-mi KWA pipeline had not even begun in April 2014.

Attempts to address the TTHM exceedances included first eliminating the softening bypass stream in an attempt to increase TOC removal (Lockwood, Andrews, & Newman 2014).

However, TTHM exceedances continued, so the anthracite media in the filters was replaced with granular activated carbon, and the ozonation system was repaired in summer 2015 (MDEQ Construction Permit W151055). TTHM levels were finally reduced, and in August 2015, only one of the eight samples taken exceeded the 80 µg/L TTHM limit (Table 1).

QUALITY OF TREATED FLINT RIVER WATER

In attempting to understand what happened in Flint, it is necessary to look not only at specific contaminants but also the general quality of the treated water. As shown in Figure 7, the pH and alkalinity of the finished water varied significantly over the 1.5 years of treatment, and for much of the time, both were quite low, especially in summer 2015. The decreases in alkalinity from June to July 2014 and over the course of the period from March to May 2015, both correspond to increases in the lime dosage (Figure 3). The reason for the change in alkalinity and pH after June 2015 is unknown, as the lime and ferric chloride dosages were fairly constant during this period. The carbon dioxide dosage may have changed during recarbonation, but the carbon dioxide dosages were not provided in the MORs.

Treatment for softening and turbidity removal, along with disinfection, reduced the alkalinity by as much as 204 mg/L as CaCO₃ and the pH by up to one log unit. The Langelier saturation index (LSI) is a measure of calcium carbonate solubility described as

$$LSI = pH + \log \left(\frac{K_a \cdot \gamma_{Ca^{2+}} \cdot [Ca^{2+}] \cdot \gamma_{HCO_3^-} \cdot [HCO_3^-]}{\gamma_{H^+} \cdot [K_{sp}]} \right)$$

where K_a is the acid dissociation constant for bicarbonate, γ is the activity coefficient, $[]$ denotes the molar concentration, and K_{sp} is the solubility product of CaCO₃. An LSI value greater than zero indicates that the solution is supersaturated and the precipitation of calcium carbonate is favored and that corrosion is less likely. An LSI value less than zero indicates that the solution is undersaturated and calcium carbonate dissolution is favored, and that the water could be corrosive if no other measures were taken to control corrosion. As a result of reductions in pH, alkalinity, and hardness during treatment, the finished water was undersaturated with respect to calcium carbonate (Figure 8). As the temperature of the water is likely to change in the distribution system (warms during winter, cools during summer), the LSI is also likely to change, suggesting that the water became more under-saturated during summer and less undersaturated during winter. The LSI would have approached -1.5 during August 2015, when the water temperature was predicted to be 15°C in the distribution system.

As shown in Table 2, the chloride content of the treated water ranged from 62 to 95 mg/L (median of 83 mg/L). The chloride level in the treated water was significantly higher than in the river water, predominantly due to the addition of ferric chloride as a coagulant. Calculations using dosing data show that the chloride levels in the treated water increased by 28–100 % as a result of the addition of ferric chloride.

The turbidity of the raw Flint River water varied seasonally (Figure 9). The turbidity of the finished water did not vary greatly (0.08–0.16 ntu), demonstrating that the filters were operating successfully. However, it can be observed that the turbidity of the water applied to the filters varied greatly, indicating the challenges plant operators had in achieving consistent performance in the upflow clarifiers. The changes in lime and polymer dosages, shown in Figures 3 and 4, likely reflect attempts to optimize the removal of turbidity.

CORROSIVE INDEXES

Although a number of indexes have been developed to provide an indication of the likelihood that corrosion or deposition will occur, none are able to predict the rate at which corrosion might occur. Nevertheless, they can be used to assess the potential effects of water quality changes on the likelihood of corrosion.

The Larson-Skold index was developed to evaluate the potential for the corrosion of cast-iron pipes transporting water from the Great Lakes (Roberge 2006). It can be used to determine the effect of chloride, sulfate, and bicarbonate/carbonate ions on the corrosivity of the treated water toward iron pipes in the distribution system. The Larson-Skold index is calculated as

$$LSI = \frac{(Cl^-) + (SO_4^{2-})}{(HCO_3^-) + (CO_3^{2-})}$$

where the concentrations are given in units of equivalents per liter. A Larson-Skold index of (1) less than 0.8 suggests that chloride and sulfate levels are unlikely to cause corrosion, (2) between 0.8 and 1.2 suggests higher than desired corrosion rates may occur, and (3) greater than 1.2 is indicative of high corrosion rates (Roberge 2006).

Unfortunately, as the sulfate concentrations were determined on only six occasions, the Larson-Skold index can be calculated only for those six days (Table 2). Of those six days, the Larson-Skold index suggests that high (sometimes very high) rates of iron corrosion should have been expected. While the number of dates are limited, the sulfate concentration was fairly constant over the 1.5 years; therefore, the values of the Larson-Skold index shown in Table 2 are likely to be indicative of the treated water during the time when the Flint River supplied the FWSC plant.

The chloride-to-sulfate mass ratio (CSMR) has been shown to be an effective tool to identify where corrosion is likely (Hill & Cantor 2011). An extensive survey of water utilities showed that 100% of utilities with a CSMR <0.58 met USEPA action limit for lead (15 µg/L) (Edwards 1999). On the contrary, only 36% of utilities with a CSMR >0.58 met the USEPA action limit (15 µg/L). If the alkalinity is less than 50 mg/L as CaCO₃, then Nguyen et al. (2010) suggested that the goal should be to achieve a CSMR in the finished water of less than 0.2. Table 2 shows that the CSMR for the treatment period was very high in all six samples. The high values of the CSMR and Larson-Skold indexes of water entering the Flint distribution system should have raised serious concerns about the possibility of corrosion,

especially given prior experience by water utilities. For example, in Columbus, Ohio, the 90th percentile lead levels in the water increased by almost 360% after a change in coagulant from alum to ferric chloride, which resulted in an increase in the CSMR by up to 170% (Hill & Cantor 2011).

SO WHAT WENT WRONG IN FLINT?

The previous discussion demonstrates the complexity of treating a variable water source. Flint River water was considered to be a challenge to treat, with “high bacteria and high carbon concentrations” that “fluxuate [sic] depending on rain events” (Mar. 20, 2012, meeting minutes, MDEQ meeting on KWA water issues). The only pilot testing that appears to have been completed before the switch was in 2002—a treatability study by Alvord, Burdick, and Howson LCC (AB&H)—and is mentioned in the OER (Lockwood, Andrews, & Newman 2015). The author of the study describes the water source as “particularly difficult to treat with seasonal variation between high organic load and high magnesium hardness” (Lawrence 2012). The treatment train recommended in the AB&H report differs significantly from that used at the Flint water treatment plant, which meant that in 2014 the plant operators lacked important information about the treatability of the water that was necessary for proper plant operation.

AWWA (Muylywyk et al. 2014) recommends that “if a municipality is considering changing how its source water is treated, the potential effects on the corrosivity of the treated water and the need for corrosion control should be evaluated.” However, sufficient pilot testing and corrosion studies were not commissioned and completed before the April 2014 switch of source waters. Furthermore, since the Flint plant had not been fully operational in almost 50 years, was understaffed, and some of the staff were undertrained, it is not surprising that it was difficult to achieve effective treatment.

Muylywyk et al. (2014) warn that any of the following treatment changes could affect corrosion or corrosion control in the distribution system:

- Process changes that result in pH or alkalinity changes
- Process changes that affect the CSMR
- Change in coagulant (the Lake Huron plant uses alum)
- Introduction of a new acid to the process (the Lake Huron plant does not use recarbonation; the Flint plant did)
- Introduction of a new base (the Lake Huron plant does not use lime; the Flint plant did)

These changes were made when Flint switched to treating the Flint River water; however, as mentioned previously, corrosion control was not used at the plant, and there was no plan for corrosion control.

As shown in Figure 7, the monthly average pH and alkalinity of the treated water were highly variable. Not shown in the figure are the changes on a daily basis. The daily pH measurements varied from 7.00 to 8.46 over the first three months of treatment. Daily

fluctuations often varied between ± 0.2 to 0.3 pH units, and as high as 1.1 log units in late April 2014. By contrast, the pH of the DWSD water varied no more than 0.34 log units over the course of a month. Changes in pH more than 0.2 units per week are not recommended (Hill & Cantor 2011), as such rapid changes in water chemistry (as experienced in the Flint system) may adversely affect system equilibrium and the passivation layer and scales on the insides of the pipes.

The red color of the water observed by Flint residents is evidence of the corrosion of iron distribution pipes. While FWSC flushed the mains by opening fire hydrants, it never seemed to address the root cause of the colored water, namely the corrosion of the iron pipes. Changes in pH and alkalinity can result in the softening of iron tubercles and therefore result in increased iron corrosion (Hill & Cantor 2011). As discussed previously, in all six samples, the Larson–Skold index was close to or greater than 1.2, indicating potentially high iron corrosion rates should have been expected. On the basis of this and the fact that no corrosion inhibitor was used, it is not surprising that significant iron corrosion was observed. In addition, bacteria are known to contribute to the corrosion of iron pipes, so it is possible that the corrosion problem was exacerbated by bacterial regrowth as a result of low chlorine residual and the likely presence of low molecular weight/easily metabolized compounds formed from the reaction of ozone with naturally occurring organic matter.

Commonly used indexes could have predicted that the treated Flint River water would likely corrode lead pipes. For example, the decision tool shown in Figure 10 uses the CSMR to predict the corrosivity of water toward lead piping. As shown in Figure 7, before July 2015, when the alkalinity of the water was greater than 50 mg/L as CaCO_3 , the CSMR values of the treated Flint River water exceeded the 0.5 cutoff, so the corrosivity of water would have been a significant concern. After this time, the alkalinity of the water was less than 50 mg/L and the CSMR greatly exceeded 0.2, indicating that lead corrosion was an even more serious concern than earlier. The addition of phosphate as an inhibitor to prevent lead corrosion is commonly used in the industry (Hill & Cantor 2011), and while the possible use of phosphate as a corrosion inhibitor was suggested (WadeTrim 2009), the reason corrosion control was not implemented is still unknown. No preliminary corrosion estimates using simple indexes appear in any of the engineering reports, and they do not appear to have been considered during the design process. Journalistic reports of the Flint disaster have often stated that the failure to add phosphate was the primary cause of the lead corrosion problem. However, it should be recognized that the CSMR of the treated Flint River water was so high that, even with the addition of phosphate, the water may have been so corrosive that lead levels in the system might have still exceeded the action level. The failure to recognize the corrosivity of the water and to add a corrosion inhibitor had devastating effects.

In the wake of the lead exposure, the MDEQ finally conducted extensive sampling and analysis of the Flint water. As of June 28, 2016, a total of 23,119 samples have been collected and analyzed for lead since September 2015. The highest lead levels measured exceeded 23,100 $\mu\text{g/L}$. On the basis of the Sentinel samples and this more extensive data set collected by the MDEQ, it appears that a significant number of premises still have high lead levels in their water (Figure 11). It has been suggested that in many cases, the high lead levels now seen in homes are due to the presence of particulate lead (USEPA 2016). This

may be the case, although at this time there appears to be limited publicly available evidence to support this supposition.

There are plans to replace all lead pipes in the Flint system. As of July 2016, lead pipes have been replaced in about 30 premises (Thomas 2016). In the case of Madison, Wis., the utility and homeowners worked together for several years to fully replace the lead service lines in every home in their service area (Corley 2016). High lead levels were found in a number of samples four years after all of the lead pipes were replaced in Madison, Wis. (Cantor 2006), suggesting that even after all the lead pipes are replaced, it may take years for the lead levels in Flint to reach a point at which the concentrations of all samples are below the action level. Clearly there is much to be done before the water crisis in Flint is over.

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Biography



Susan J. Masten has 35 years' experience in water treatment and 27 years at Michigan State University. She holds a patent on a hybrid ceramic membrane filtration system and has conducted extensive research on the use of this technology for the control of disinfection by-products, nanoparticles, bromate, and pharmaceuticals in drinking water. Masten earned a BS degree in biochemistry from Fairleigh Dickinson University, Teaneck, N.J.; an MSE degree in environmental engineering from West Virginia University in Morgantown, W.V.; and a PhD degree in environmental engineering from Harvard University, Cambridge, Mass.

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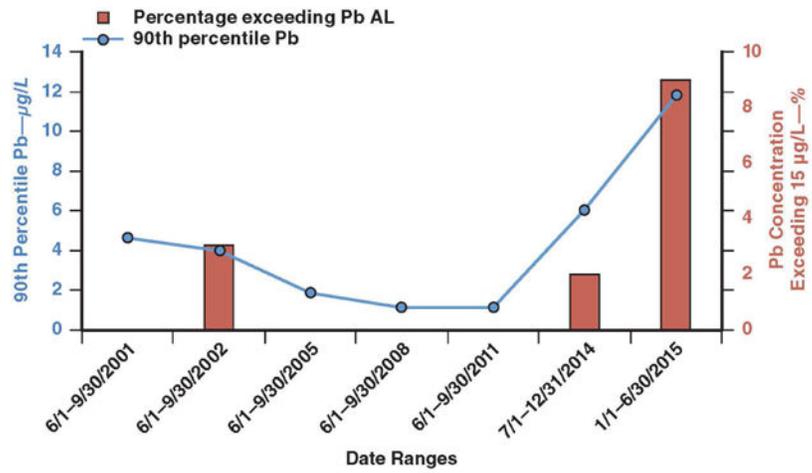
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Sampling and analyses were required for compliance with the Lead and Copper Rule.

AL—action level, Pb—lead

FIGURE 1.
Historical data for lead concentrations in the Flint distribution system

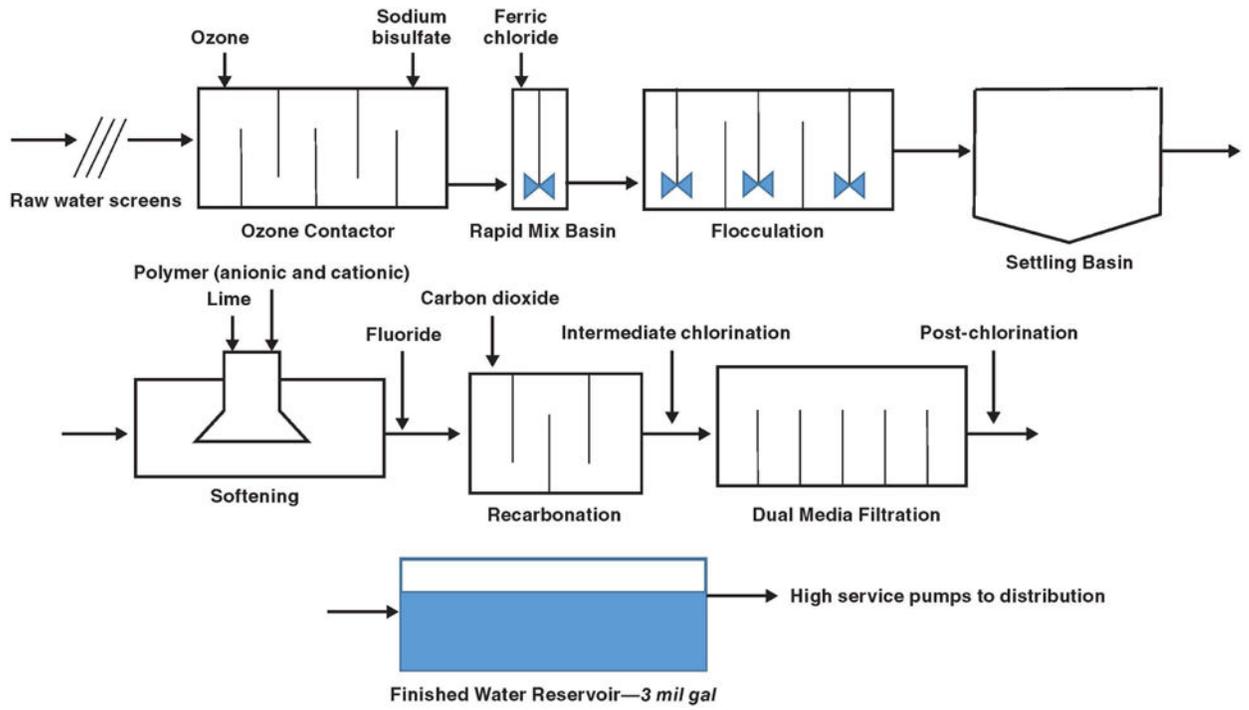
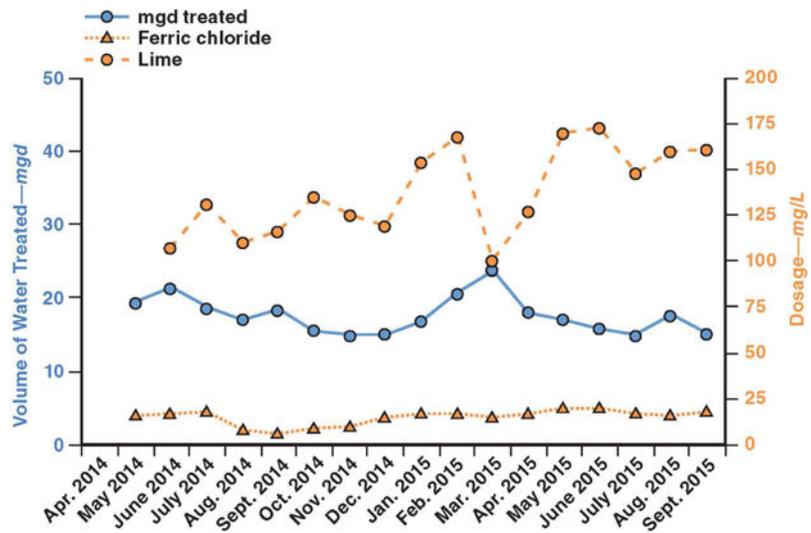


FIGURE 2.
Schematic of the Flint Water Treatment Plant



The volume of water treated (mgd) is given for comparative purposes.

FIGURE 3. Variability in the monthly average ferric chloride (as Fe³⁺) and lime dosages used at the Flint water treatment plant for 1.5 years

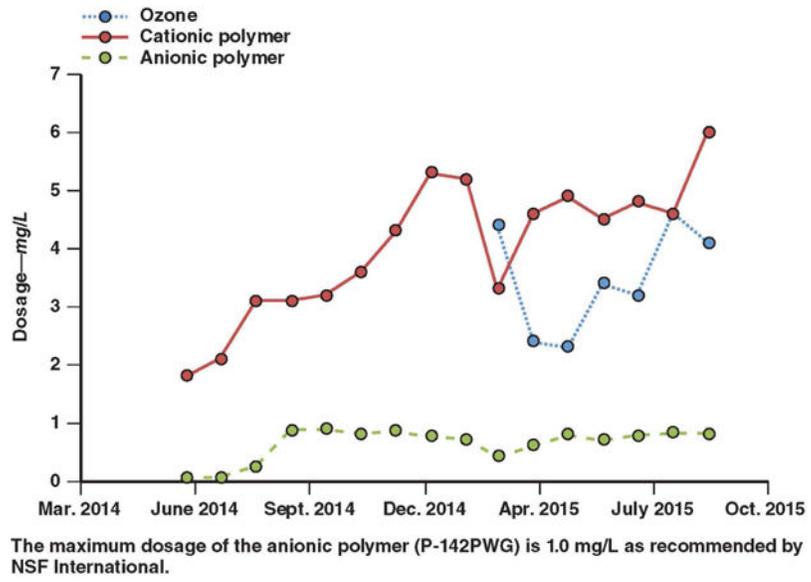


FIGURE 4. Variability in the monthly average ozone and polymer dosages used at the Flint water treatment plant for 1.5 years

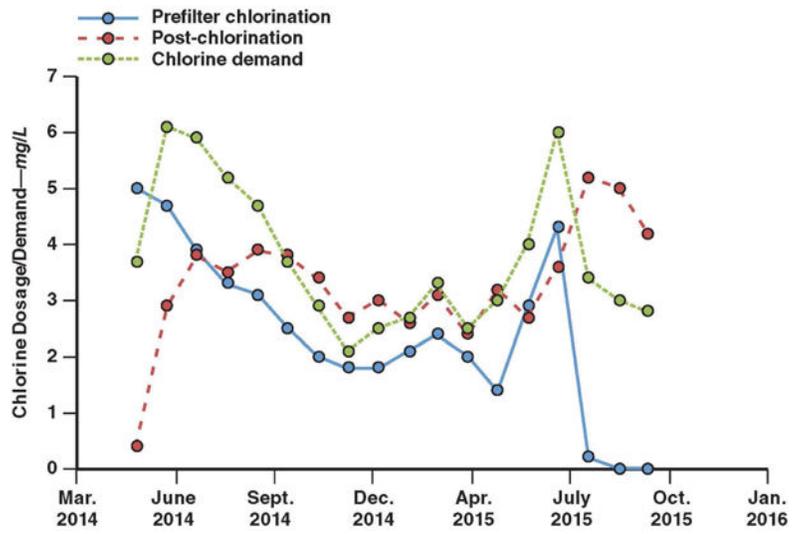


FIGURE 5. Applied chlorine dosages and chlorine demand of treated Flint River water

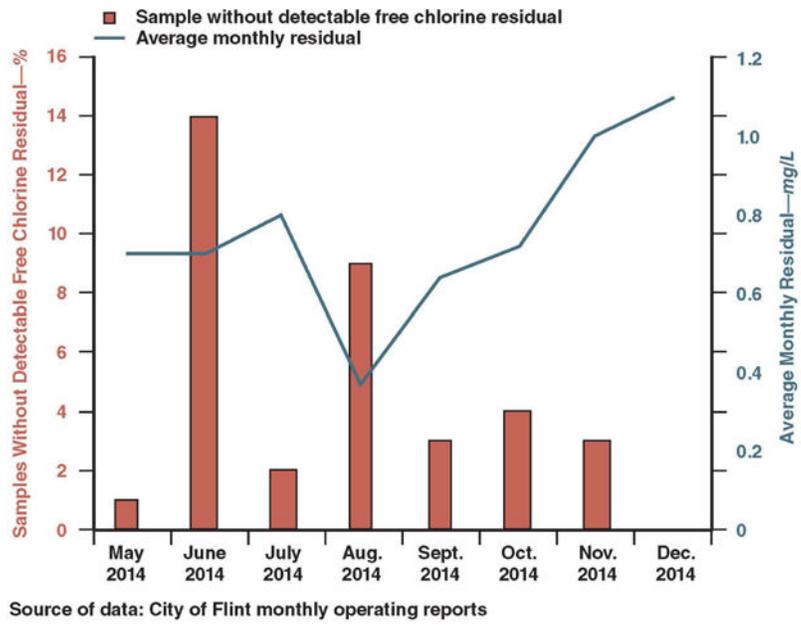


FIGURE 6.
Chlorine residuals at monitoring sites in the Flint distribution system

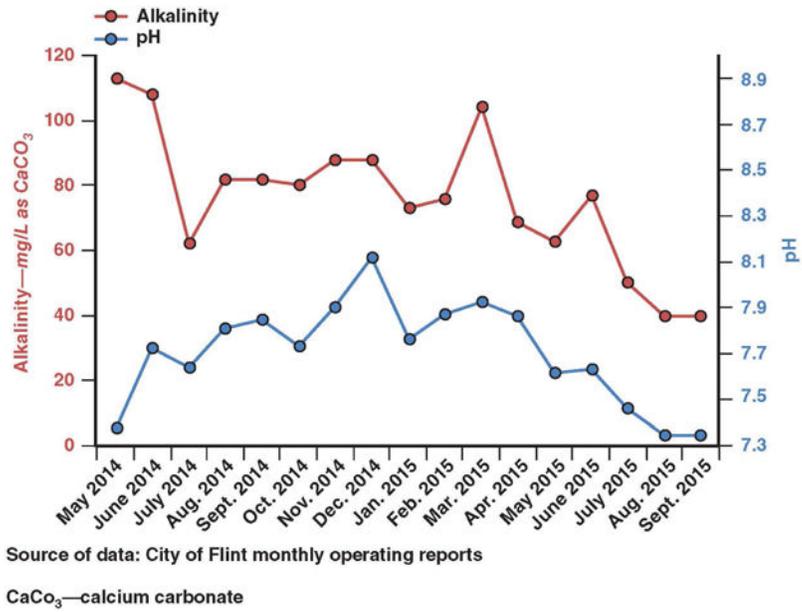


FIGURE 7.
Monthly average pH and alkalinity in the treated Flint River water

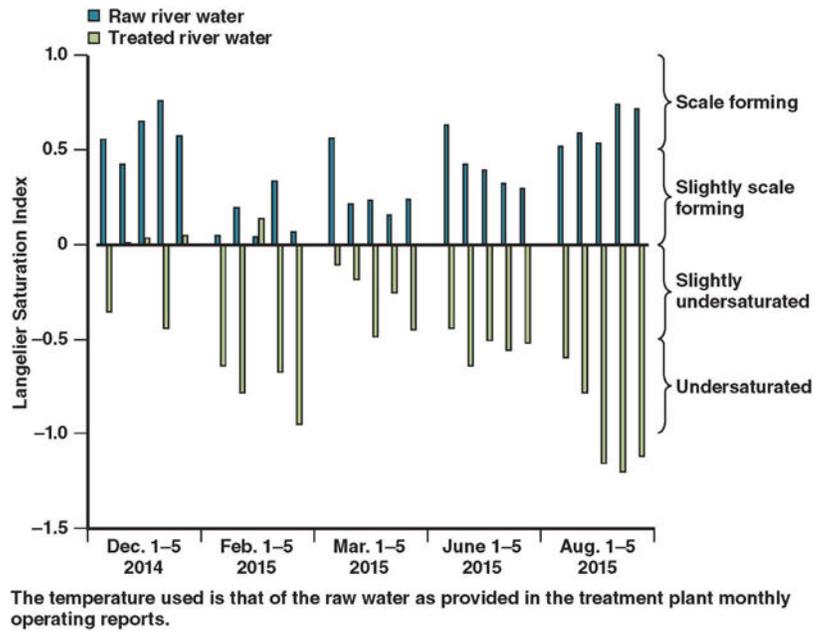


FIGURE 8. Langelier saturation index of the treated Flint River water at various times during the treatment period

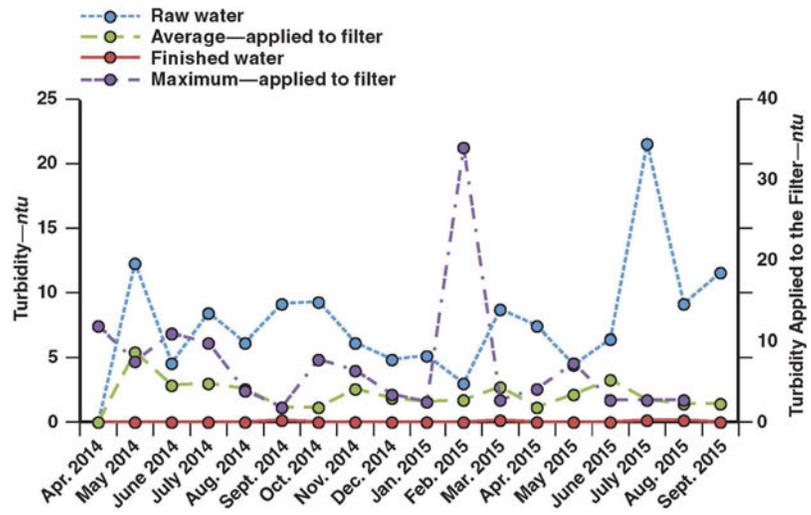


FIGURE 9. Variability in turbidity within the Flint water treatment plant

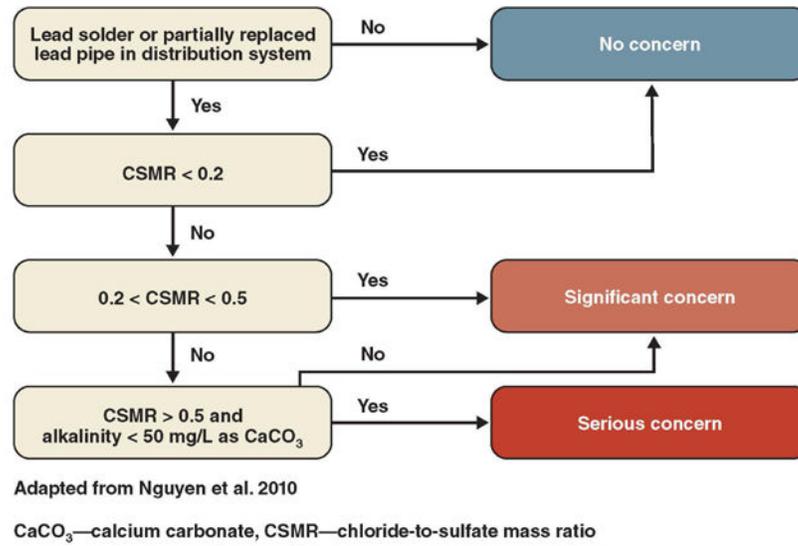
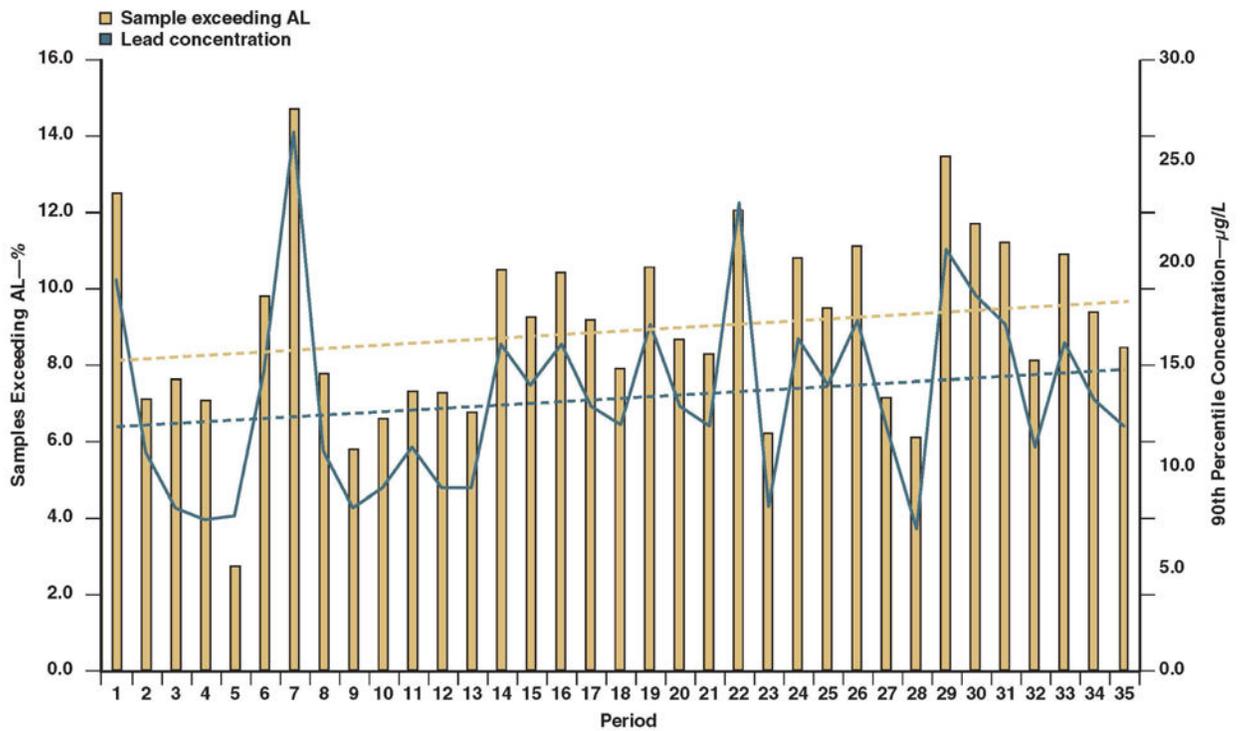


FIGURE 10.
Decision tool to assess corrosion potential based on CSMR



AL—action level

^aDetermined from the Michigan Department of Environmental Quality sampling efforts from Sept. 1, 2015, through July 23, 2016

Period	Date
2015	
1	September
2	Oct. 1–15
3	Oct. 16–31
4	November
5	Dec. 1–10
6	Dec. 11–31
2016	
7	Jan. 3–9
8	Jan. 10–16

Period	Date
9	Jan. 17–23
10	Jan. 24–30
11	Jan. 31–Feb. 6
12	Feb. 7–13
13	Feb. 14–20
14	Feb. 21–27
15	Feb. 28–Mar. 5
16	Mar. 6–12
17	Mar. 13–19
18	Mar. 20–26

Period	Date
19	Mar. 27–Apr. 2
20	Apr. 3–9
21	Apr. 10–16
22	Apr. 17–23
23	Apr. 24–30
24	May 1–7
25	May 8–14
26	May 15–21
27	May 22–28
28	May 29–June 4

Period	Date
29	June 5–11
30	June 12–18
31	June 19–25
32	June 26–July 2
33	July 3–9
34	July 10–16
35	July 17–23

FIGURE 11. Percentage of samples exceeding the lead AL of 15 µg/L and the 90th percentile lead concentration^a

TABLE 1

Total trihalomethane (TTHM) concentrations in the Flint distribution system

Location	TTHM concentration $\mu\text{g/L}$			
	May 21, 2014	Aug. 21, 2014	Nov. 21, 2014	Aug. 18, 2015
1	162.4	145.3	58.6	67.9
2	75.1	112	36.2	53.6
3	111.6	127.2	33.3	60.2
4	79.2	181.3	33.9	72.0
5	106.4	196.2	93.6	93.5
6	82.2	112.4	50.1	65.9
7	88.2	144.4	53.6	69.4
8	96.5	118.3	41.1	54.9

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Parameter concentrations used to characterize the likelihood of corrosion and associated CSMR and Larson-Skold indexes in the treated Flint River water

TABLE 2

Sample Date	Concentration <i>mg/L</i>		Concentration <i>mg/L</i> as CaCO_3	Alkalinity	CSMR	Larson-Skold Index
	Cl^-	SO_4^{2-}				
May 22, 2014	85	25	118	3.8	1.24	
Aug. 6, 2014	65	23	60	2.8	2.31	
Oct. 28, 2014	62	22	76	2.8	1.45	
Feb. 16, 2015	95	25	47	3.8	3.40	
May 12, 2015	90	31	56	2.9	2.84	
Aug. 11, 2015	81	21	36	3.8	3.78	

CaCO_3 —calcium carbonate, Cl^- —chloride, CSMR—chloride-to-sulfate mass ratio, SO_4^{2-} —sulfate