Chlorinated Water Line Breaks: Decay and Ecological Impact in Austin Creeks

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Abstract

Chlorine from potable (drinking) water distribution line breaks or releases during maintenance has the potential to be toxic to aquatic life. EPA estimates a 1-hour no observed adverse effects concentration (NOAEC)of 0.011 mg/L total residual chlorine if spill recurrence interval is at least 3 years. The average chlorine concentration in drinking water distribution system is 1.9 mg/L. Monitoring data from six drinking water line breaks was used to estimate an average chlorine concentration decay with overland distance traveled of -0.00021 mg/L/ft. This information will be used in the Barton Springs Catastrophic Spill Plan(BSCSP) in development of a chlorinated water line spill response strategy. This strategy, which can also be used citywide will consider the relationship of chlorinated water volume to receiving water volume (dilution) and distance from chlorinated water source to receiving water (decay) in comparison to allowable instream chlorine concentrations. Equations to estimate dilution and decay are presented.

Introduction

The use of chlorine by drinking water utilities to prevent waterborne diseases has been practiced for over a century. Due to its low cost and high effectiveness, chlorine is the most widely used water disinfectant in potable water treatment (Bhardwa 2006). According to the Water Industry Data Base, 237,600 water main breaks occur annually in the United States with an average of 0.27 water main breaks per mile of pipe per year (Kirmeyer *et al.* 1994). Chlorine from potable water distribution line discharges to the environment are often at concentrations toxic to aquatic life. When released into the environment and combined with organic matter chlorine forms a variety of disinfection by-products (DBP). These by-products are potentially carcinogenic to humans (USEPA 2001) and have caused impaired neurological development, oxidative stress and cancer in laboratory animals (WHO 2008). The two major DBP groups present in freshwater are trihalomethanes (THMs) and haloacetic acids (HAA) (Bhardwa 2006). Formation of these DBPs varies and is based on the temperature, time, and pH of the water (Bhardwa 2006). Stewart *et al*. (1996) found that in-situ changes in total residual chlorine (TRC) concentrations were three times higher at night than during the day and depended on light and periphyton availability. This high reactivity and variability of chlorine in solution makes predicting ecological impacts difficult and provides challenges for spill responders. Water utilities using combined chlorine (chloramines as used by the Austin Water Utility) may also be releasing ammonia into the environment during drinking water line breaks. Total ammonia concentrations for combined chlorine disinfection systems generally are less than 0.5 mg/L and the most recent average published by the Austin Water Utility was 0.54 mg/L, which is lower than the lowest EPA 1-day average concentration limit for ammonia of 0.58 mg/L. This study does not consider ammonia from drinking water line spills, but these releases could be evaluated for specific environments with more sensitive ecological receptors. A brief review of potential environmental impacts relative to Austin streams is provided with suggested approaches for spill response. Specific potential impacts and response strategies to protect the Barton Springs Salamander have been detailed separately and will be included in subsequent drafts of the Barton Springs Catastrophic Spill Plan (BSCSP) (Turner and O'Donnell 2005; Herrington and Turner 2009; COA, 2010).

Impacts to Aquatic Life

The current guideline for protecting aquatic organisms from chlorine toxicity was established in 1986 by U.S. Environmental Protection Agency (USEPA). Aquatic organisms, unless locally important and sensitive, should not be affected unacceptably if the 4-day average concentration of TRC does not exceed 0.011 mg/L and/or the 1-hour average concentration does not exceed 0.019 mg/L more than once every 3 years (USEPA 1986). Three years is the recommended average amount of time needed for an unstressed system to recover from a pollution event where exposure to chlorine exceeded the criterion (USEPA 1986). Studies that impacted this decision found a wide range of sensitivities to different freshwater species. Thirty-three species from 28 different genera had been tested and showed both acute and chronic responses to TRC exposure (USEPA 1986). Acute toxicity ranged from 0.028 mg/L for *Daphnia magna* to 0.710 mg/L for the threespine stickleback fish with chronic toxicity occurring as low as 0.0034 mg/L (USEPA 1986). Additional exposure studies have shown that species richness of protozoans was reduced by 20% with exposure to 0.0027 mg/L TRC (Cairns *et al.* 1990) and that glochidia of the Oyster Mussel (*E. capsaeformis*) experienced significant declines in growth and survivorship after 21 day exposure to 0.020 mg/L TRC (Valenti *et al.* 2006). Susceptibility of Oyster Mussels to chlorine toxicity was highest with 3 month old glochidia and significantly declining with increased age (Valenti *et al.* 2006). Although this mussel does not occur in Austin, freshwater mussels (Unionidae) are found in multiple Blackland Prairie streams in eastern Austin and in the Colorado River and its reservoirs (Perry et al 2010). Freshwater mussels have been found in streams containing or dominated by wastewater effluent (e.g., Wilbarger Creek), and these streams have shown a measurable total chlorine concentration despite dechlorination of effluent (COA, unpublished data). One sensitive species of concern is the federally-listed endangered Barton Springs Salamander (*Eurycea sosorum*). Total chlorine toxicity tests on a surrogate species, *Eurycea nana*, yielded a 48-hour no observed effects concentration (NOEC) of 0.0625 mg/L and a 48-hour LC_{50} concentration of 0.088 mg/L. Again, chlorinated water line impacts to the Barton Springs Salamander are addressed in detail in development documents and will be included in subsequent drafts of a specific spill response plan (Turner and O'Donnell 2005; Herrington and Turner 2009, COA 2010).

Chlorine in the Environment

Chlorinated waters from potable treatment and distribution systems can enter the environment through water main breaks, disinfection of new mains, distribution system maintenance, water main flushing, filter backwash and other utility operations (Tikkanen *et al.* 2001). A typical chlorine concentration in a drinking water distribution line in Austin is 1.9 mg/L, although TRC concentrations of 2.52 mg/L on average are reported at the Austin Water Utility treatment plant before chlorinated water enters the distribution system. Chlorine concentrations are expected to decrease within the distribution system with increasing distance from the treatment plant. Once in the environment, chlorine's high oxidation potential causes initial reactions with natural organic matter (NOM) to occur quickly (Gang *et al.* 2003). Sirivedhin and Gray (2005) found that surrogates for measuring chlorine's specific reactive sites with NOM to produce DBP's in aquatic environments are: total organic carbon (TOC) content, ultraviolet absorbance (254 nm and 272 nm), ratio of Dissolved Organic Carbon (DOC) to absorbance at 260 nm, and fluorescence spectral data. Predicting decay rates and corresponding impacts to the aquatic community by chlorine is difficult because first order models cannot describe the entire process (Gang *et al.* 2003). Brungs (1973) discusses how Rainbow Trout exposed to concentrations ranging between 0.014 – 0.029 mg/L TRC experienced a 50 % reduction in number after 96 hours of exposure in receiving streams of a disinfected waste water discharge with some fish death occurring as far as 0.8 miles downstream. Water samples that have higher anthropogenic influences, specifically effluent-derived organic matter (EfOM), have higher overall DBP formation potential (Sirivedhin and Gray 2005) and thus pose increased risks. Understanding the length and duration of impacts caused by chlorinated discharge is important for spill response teams and water utility managers.

Chlorine decay may be described as a first-order reaction over time (Abdel-Gawad and Bewtra 1988). Neglecting evaporation and photolysis and assuming turbulent flow conditions at a temperature of 20 ºC, chlorine decay may be predicted as:

$$[\text{Chlorine, mg/L}] = 1.9e^{-0.133*t} \quad \text{where } t\!=\!\textit{time} \text{ in days}$$

An alternate method may be derived from the Worthington equation which relates the mass of dye injected into a Karst aquifer to spring discharge concentrations (Worthington and Smart, 2003):

$$c = 1.38\ m^{1.03093} / tQ$$

where:

m is the mass of dye injected in grams,
t is the time elapsed between injection and peak recovery in seconds,
Q is the output discharge in m^3/s, and
c is the peak recovery dye concentration in g/m^3

These equations may be most applicable for estimating sub-surface transport through the aquifer when travel time may be estimated from dye tracing. Travel time estimation for surface flow over any significant distance during emergency response investigation is extremely difficult as multiple channel cross sections, antecedent flow conditions and substrate types are encountered.

Monitoring Data Summary

Chlorine decay based on overland distance traveled may be estimated empirically, although volume of chlorinated water discharge and type of surface may affect measured decay rates. City of Austin Spill and Complaint Response Program staff (SCRP) measured total chlorine concentrations with a field test kit at varying distance from the source of the water line break for six events (Table 1). All spills started on pavement and ended on natural (rock, soil) surfaces. Chlorine decay with distance was estimated by linear regression for each event (Figure 1).

Table 1. Summary of SCRP monitoring events.

Date	# Samples	Broken Line Diameter (in)	Total Distance Traveled (ft)
14-Aug-2006	5	8	3,628
11-Dec-2006	5	6	7,323
12-Jan-2007	4	6	2,738
06-Oct-2006	7	unknown	4,618
17-Mar-2007	3	unknown	3,911
03-Aug-2006	12	unknown	2,065

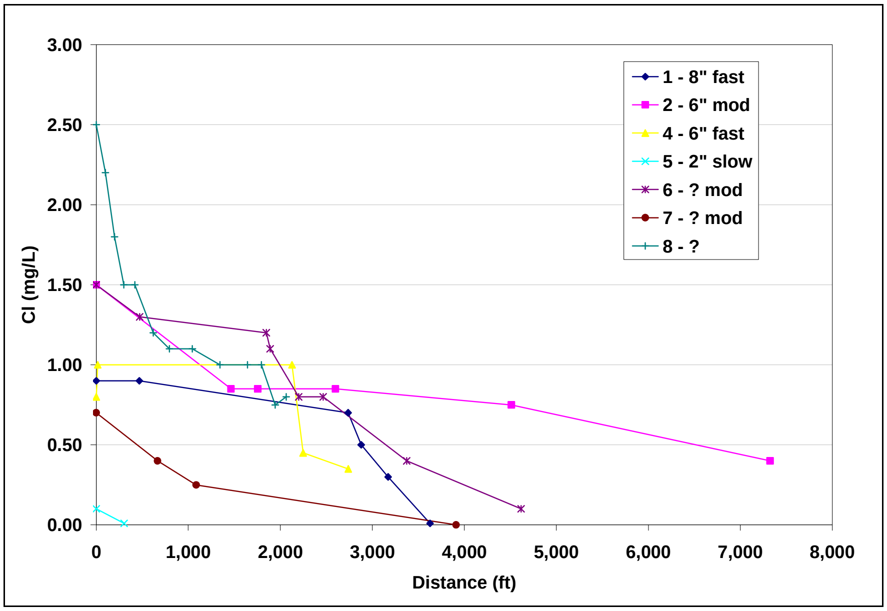

Figure 1. Loss of total chlorine versus distance traveled as measured by SCRP staff for 6 events.

Average chlorine loss rate slopes for multiple surface types were calculated (Table 2). Decay is greatest for flows over natural surfaces (non-pavement) most likely due to increased contact with organic material and decreased linear velocity due to friction. The differences in estimated decay between flow in enclosed pipes and over pavement are most likely due to sunlight. The concentration decay with travel distance is only representative of initial conditions. As the duration of the water line break flow increases, decay rates may decrease as available organic material becomes saturated and ambient water in the channel is replaced by chlorinated water. The overall average decay rate of -0.00021 mg/L/ft is considered to be generally representative for a typical distribution line spill flowing over multiple surface types. Chlorine decay may be estimated as:

$$\text{Final chlorine, mg/L} = \text{Initial chlorine, mg/L} - 0.00021 * (\text{Distance, ft})$$

Table 2. Chlorine decay with flow path distance slopes from linear regression.

Surface Type	Chlorine decay (mg/L/ft)
Enclosed Pipe	-0.00019
Pavement	-0.00023
Natural Surface	-0.00041
Overall Average	-0.00021

The Austin Water Utility measures residual chlorine in the drinking water distribution system at selected locations to verify regulatory compliance. Between 1 November 2008 and 31 October 2010, chlorine residual was measured in 7,151 samples from the distribution system at 263 locations. The site average of chlorine residual was 1.92 mg/L with site averages ranging from 0.92 mg/L to 2.3 mg/L. The Austin Water Utility uses chloramines for the disinfection; therefore the total chlorine residual values are effectively equal to combined chlorine, as no free chlorine is present (Susan Davis, Austin Water Utility personal communication, 5 November 2010). Chlorine concentrations at individual tap locations are relatively constant. For the November 2008 to October 2010 time period, monitoring locations with at least 24 measurements yielded an average percent coefficient of variation of 15.8%, with a 75th percentile value of 16.9% COV. Average chlorine concentrations vary between sites in the distribution system, generally decreasing at the periphery of the service area (Figure 2).

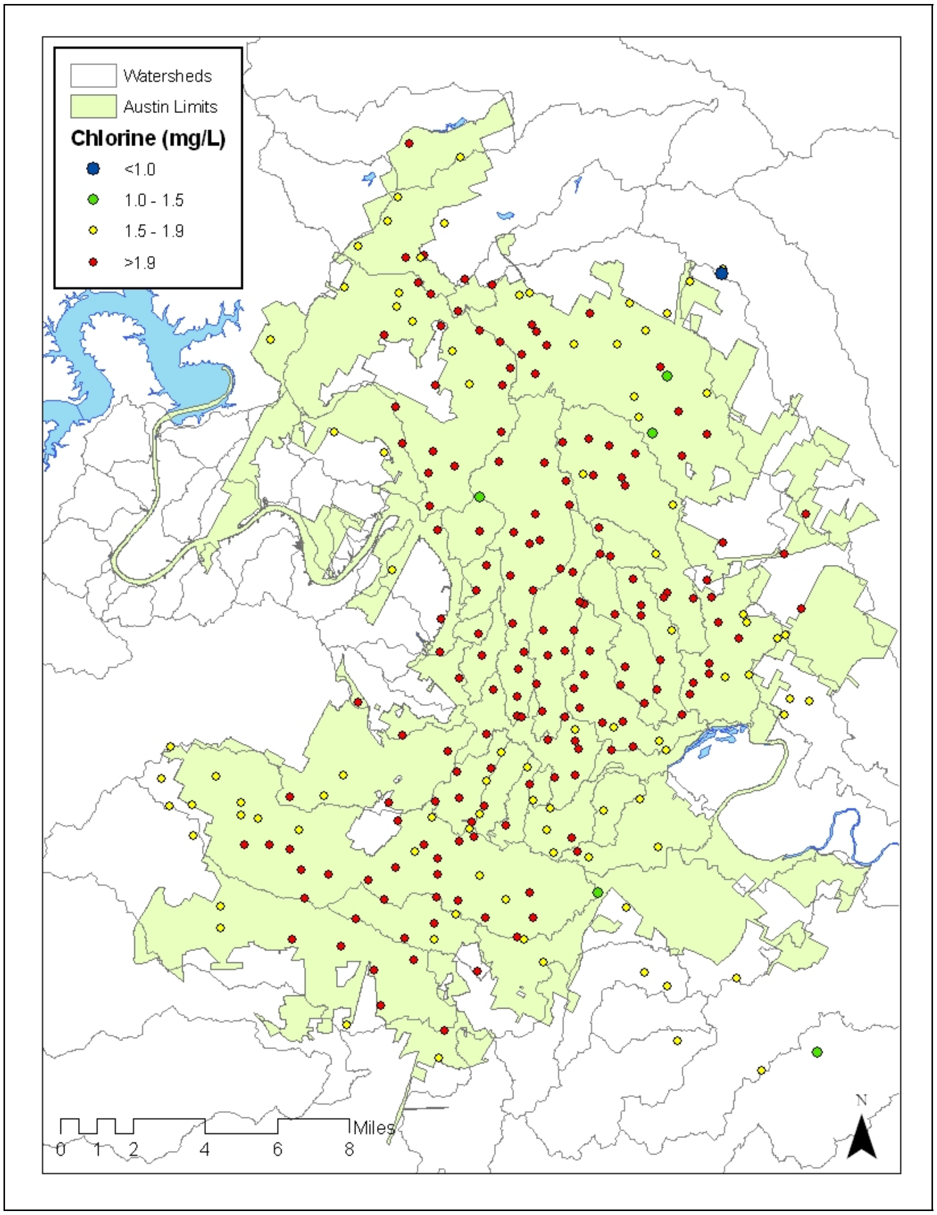

Figure 2. Site average chlorine concentration within the drinking water distribution system, based on at least 24 measurements from November 2008 to October 2010.

Impacts of Dechlorination

Sodium thiosulfate ($Na_2S_2O_3$) is a preferred chemical dechlorination agent as it scavenges less dissolved oxygen (DO) than other popular dechlorination chemicals and is not particularly toxic to aquatic species (Tikkanen *et al.* 2001). Ascorbic acid is an alternative dechlorination agent, requiring 2.5 parts of ascorbic acid to neutralize 1 part of chlorine, more than required by sodium thiosulfate (Tikkanen *et al.* 2001). Although not consuming DO, the weak acidity of ascorbic acid should be evaluated against the ambient pH range of the target system prior to use. For general environmental conditions, addition of sodium thiosulfate up to 2 times the stoichiometric requirements for treatment of 1.5 mg/L chlorine may exert approximately a 1.0 mg/L DO demand (Tikkanen *et al.* 2001). If properly dosed, oxygen demand from use of sodium thiosulfate to dechlorinate is not likely to cause DO concerns under most ambient conditions. Overdosing of sodium thiosulfate can exert a significant oxygen demand, and doses should be monitored or in-stream dissolved oxygen concentrations monitored to assure that DO concentrations after dechlorination remain above 5 mg/L.

Considerations for Spill Response

A substantial amount of chlorine may be released from a distribution line (Table 3), particularly in relation to nominal stream flow in critical summer conditions in Austin where median flow concentrations are often less than 1 ft^3/s. In evaluating resulting instream concentrations, two key factors must be evaluated: (1) dilution: relationship between flow rate of drinking water line to flow rate of receiving water body; (2) decay: distance from drinking water spill to receiving water body. Antecedent flow conditions may be accounted for by the dilution ratio calculation. Improvements to the decay rate procedure could be made by incorporating time of travel in lieu of distance, and the use of overland flow surface type. In general, the more flow from a chlorinated water line that can be directed overland (without creating excessive soil erosion) or in open (sun-exposed) dry conveyances, the more chlorine will be consumed, the less dechlorination will be required, and the less potential harm to aquatic life.

Table 3. Potential Discharge* from Broken Water Mains pressurized at 90 lb/in^2.

pipe diameter (in)	gal/min	ft^3/s	gal/hour
1	198	0.4	11,880
2	792	1.8	47,520
3	1,783	4.0	106,980
6	7,131	15.9	427,860
4	3,169	7.1	190,140
8	12,677	28.2	760,620
12	28,524	63.6	1,711,440
16	50,708	113.0	3,042,480
24	114,094	254.2	6,845,640
30	203,818	397.2	10,696,320
36	178,272	572.0	15,402,660
48	456,376	1017.0	27,382,560
60	713,087	1589.0	42,785,220
72	1,026,846	2288.2	61,610,760

*Greeley equation for roughly circular holes: $Q\ (gpm) = 30.394 * area\ (in^2) * \sqrt{[pressure\ (lbs/in^2)]}$.

The target chlorine concentration in the receiving water is assumed to be the EPA 1-hour 0.019 mg/L NOEC estimate, and the assumed concentration of total chlorine in the distribution system is estimated to be 1.9 mg/L. Only flowing water bodies or water bodies with pools that support aquatic life merit additional action. One potential definition suggested for water bodies in Austin that are likely to support pools that are significant refugia for aquatic life is any channel with a 64 acre or larger drainage area.

Given the decay relationship, any chlorinated water line break that flows a distance of less than 8,730 ft before reaching a flowing water body or existing pool may require additional action:

Calculation of the chlorine concentration at the point it enters the receiving water based on the estimated overland flow distance is suggested as:

$$[\text{Chlorine at receiving water before mixing, mg/L}] = 1.9 - 0.00021 * (\text{distance, feet})$$

Calculation of the dilution of chlorine in the receiving water, preferably using estimated relative discharge (flow) measurements for the water line break (Q_{break}) and the receiving water (Q_{stream}) (alternately the estimated relative volumes (length * width * depth) of water from the water line break and water in the receiving water can be used if discharge cannot be measured):

$$[\text{Chlorine in receiving water after mixing, mg/L}] = [\text{chlorine after decay, mg/L}] * Q_{break} / (Q_{break} + Q_{stream})$$

If the chlorine concentration exceeds 0.019 mg/L, then dechlorination to 0.019 mg/L is warranted. These rules could be automated in GIS using buffer analysis of stream centerlines in combination with Austin Water Utility drinking water line size and location to flag all lines that, if damaged or submitted for maintenance, trigger notification to the SCRP team and (or) include a recommended course of action. These buffers could be adjusted based on the site-specific average chlorine concentration in the distribution system (Figure 2).

References

Abdel-Gawad, S.T., and J.K. Bewtra. 1988. Decay of chlorine in diluted municipal effluents. Canadian Journal of Civil Engineering 15(6): 948-954.

Bhardwaj, V. 2006. Disinfection By-products: Technical brief. Journal of Environmental Health

Brungs, W. 1973. Effects of Residual Chlorine on Aquatic Life. Water Pollution Control Federation, Vol. 45, No. 10

Cairns, J., Niederlehnera, B., Pratt, J., 1990. Evaluation of joint toxicity of chlorine and ammonia to Aquatic Communities. Aquatic Toxicology. Vol 16, No. 2.

Cityof Austin. 2010. Barton Springs Catastrophic Spill Plan, Watershed Protection Department, Environmental Resource Management Division, Austin, Texas.

Gang, D., Clevenger, T., Banerji, S. 2003. Modeling Chlorine Decay in Surface Water. Journal of Environmental Informatics. Vol 1, No. 1.

Herrington, C., and M. Turner. 2009. Drinking water distribution line break impacts on Barton Springs Salamander. City of Austin Watershed Protection and Development Review Department. SR-09-03.

Kirmeyer, G., Richards, W., Smith, C. 1994. An Assessment of Water Distribution Systems and Associated Research Needs. Denver, CO: AWWARF.

Perry, H., and T. Jackson, M. Scoggins. 2010. Inventory of freshwater mussels (Unionidae) in Austin, Texas. City of Austin Watershed Protection Department. SR-11-02.

Sirivedhin, T., and Gray, A. 2005. Comparison of the disinfection by-product formation potentials between a wastewater effluent and surface waters. Water research. Vol 39, pp. 1025-1036

Stewart, A., Hill, W., Ham, K., Christensen, W. 1996. Chlorine Dynamics and Ambient Toxicity in Receiving Streams. Ecological Applications, Vol. 6, No. 2.

Tikkanen, M., Schroeter, J., Leong, L., Ganesh, R. 2001. Guidance Manual for Disposal of Chlorinated Water. American Water Works Association

Turner, M., and L. O'Donnell. 2005. Response tier development document: Barton Springs Salamander Catastrophic Spill Plan. City of Austin Watershed Protection and Development Review Department. SR-05-01.

U.S. Environmental Protection Agency (USEPA). (2001). Controlling Disinfection By-Products and Microbial Contaminants in Drinking Water. EPA/600/R-01/110.

U.S. Environmental Protection Agency (USEPA). (1986). Quality Criteria for Water. EPA 440/5-86-001

Valenti, T., Cherry, D., Currie, R., Neves, R., Jones, J., Mair, R., Kane, C. 2006. Chlorine Toxicity to Early Life Stages of freshwater Mussels (Bivalvia: Unionidae). Environmental Toxicology and Chemistry, Vol. 25, No. 9, pp. 2512–2518,