Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2012.698816

48 (2012) 215–220
October

Comparative monitoring study of reverse osmosis vs lime softening for THM levels in water distribution systems and cul de sacs

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Received 16 October 2011; Accepted 12 April 2012

ABSTRACT

The City of Miramar, located in South Florida, has two water treatment plants which utilize two different water treatment processes. The East Water Treatment Plant (EWTP) uses lime softening, while the West Water Treatment Plant (WWTP) uses reverse osmosis treatment. Biscayne aquifer is used as the source water for both plants. Effectiveness of lime softening and reverse osmosis processes were evaluated in terms of trihalomethane (THM) levels in the distribution system with distance and at cul de sacs (dead end streets). The water treated by lime softening had significantly higher levels of THMs in comparison to the water treated by reverse osmosis. With the aging of reverse osmosis membranes (after 5 years), the THM levels exhibited similar levels in both distribution systems. The THM concentrations at the cul de sacs receiving water treated by lime softening were significantly higher in comparison to the system wide water quality. At the cul de sacs receiving water treated by reverse osmosis, THM levels were similar to the system wide water quality. Distance from the treatment plant was not a significant factor for THM levels in the water distribution system.

Keywords: Trihalomethanes; Residual chlorine; Water distribution; Cul de sac; Reverse osmosis; Llime softening

1. Introduction

Municipal water supply systems provide potable water that is safe for human consumption and adequate quality for industrial users. Currently, the commonly used drinking water treatment processes for surface and groundwater treatment involve chemical/physical processes which include coagulation, flocculation, sedimentation, and filtration steps followed by disinfection to inactivate any pathogenic microorganisms. Although lime softening is not a process typically used to remove natural organic matter (NOM), it can remove a significant fraction of NOM. Also, when magnesium hydroxide ($Mg(OH)_2$) is precipitated at high pH conditions, NOM removal could be significant since magnesium hydroxide ($Mg(OH)_2$) acts like a coagulant [1]. The process of improved removal of precursors of disinfection byproducts (DBP) such as NOM by precipitative softening is referred to as enhanced softening. Effectiveness of softening by precipitation for NOM removal has been investigated with bench-scale studies [2–6]. Johnson and Randtke [2] examined the removal of total organic carbon (TOC) with bench-scale lime softening experiments for different source waters. Softening with post chlorination resulted in TOC reductions of 14% and 32% for a river water and groundwater, respectively. Liao and Randtke [3] observed that NOM

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removal during the precipitative softening process was primarily achieved by adsorption onto calcium carbonate and magnesium hydroxide. Therefore, NOM removal depends on the calcium carbonate ($CaCO_3$) and magnesium hydroxide ($Mg(OH)_2$) levels during the softening process. The authors suggested a two-stage process for effective removal of both NOM and hardness.

Membrane processes can remove DBP precursors through filtration. Hydrated size, shape and chemical characteristics of organic compounds play important roles in permeation of NOM through the membrane [7]. Microfiltration and ultrafiltration can typically achieve between 5% and 30% NOM removal. Typically nanofiltration and reverse osmosis can achieve NOM removals between 50% and 99%. TOC removals of 70–95% are commonly achieved with nanofiltration (NF) and reverse osmosis systems (RO) [8]. However, membranes with larger molecular weight cut off (MWCO) are not as effective for removing DBP precursors. Some studies have shown that ultrafiltration membranes with MWCO of 1–2 kDa can achieve as much as 83% removal of humic substances [9].

Chlorination is widely used in water treatment to control water quality and prevent epidemic occurrences of diseases which are transmitted by water (i.e., cholera). For controlling the water quality during water distribution, residual levels of disinfectants are left to ensure continued disinfection potential. However, NOM present in the source water can result in formation of trihalomethanes (THMs) in the finished water. Experimental and empirical studies indicate that there is a strong correlation between THM formation and chlorine dosage [10]. Total THMs (also known as THM4) include chloroform ($CHCl_3$), dichloro-bromo-methane ($CHCl_2Br$), chloro-dibromo-methane ($CHClBr_2$) and bromoform ($CHBr_3$). Maximum contamination level (MCL) set by US Environmental Protection Agency (US EPA) is the sum of these four constituents. THM levels less than 80 μg/L are acceptable in the distribution system. Studies with high dosages of DPBs have shown evidences of carcinogenicity, nephrotoxicity, developmental toxicity, reproductive defects, and neurological effects [11].

The THM levels in distribution systems can be estimated using kinetic models based on the contributing factors for the THM formation (i.e., chlorine and NOM) [12–14]. In laboratory studies of DBP formation in different water sources (river basin and ground water) from two plants in Romania showed that groundwater forms less THM4 than the surface water [15]. The temporal and spatial effects within a distribution system (DS) indicate that formation of THM4 depends on seasons and temperature [16,17]. The age and chlorine profile, which affect THM formation within the distribution system [16,17], can be estimated by computer models such as EPANET [18]. The laboratory studies of chlorine decay by nitrification indicate persistence of choloroamines. However, in the presence of nitrifying bacteria, the chloroamine is less effective in controlling the bacterial growth [19]. Presence of organic and inorganic constituents affect chlorine dissipation and its effectiveness during treatment [20].

The City of Miramar located in South Florida, has a population of over a 100,000 people. The City operates two water treatment plants with two different treatment processes. The East Water Treatment Plant (EWTP) uses lime softening process while the West Water Treatment Plant (WWTP) uses reverse osmosis treatment. Both plants use a groundwater well to extract water from the Biscayne aquifer. The purpose of this study was to compare the THM levels (as chloroform) in the areas served by the East (lime softening) and West (reverse osmosis) water treatment plants. The effectiveness of lime softening and reverse osmosis processes were compared in terms of formation of THMs in the distribution system with distance and at cul de sacs (dead ends). Since bromine is not present in the raw water, only chlorine species were monitored. The DBP rule promulgated by US EPA in January 4, 2006 requires all municipalities to comply with current DBP standards for THMs and haloacetic acids (HAAs) [21]. The acceptable THM levels are below 80 μg/L. The objective of the new rule is to lower the exposure of the residents to high levels of THMs. The changes include the DBP calculations in the local running annual average of the quarterly samples for each DBP monitoring location.

2. Methods

2.1. Characteristics of the East and West Plants

The East Water Treatment Plant (EWTP) was built in 1954 and provides about 5 MGD (19,000 m^3 d^{-1}) potable water. The plant uses lime softening process consisting of coagulation, flocculation, sedimentation and filtration steps (Fig. 1a). Oxidation prior to coagulation is used to control color and algae formation. Chlorine in the form of sodium hypochlorite at 12% is added for disinfection and ammonia is added to reduce the formation of DBPs in the distribution system. The addition of ammonia is to comply with the health department change of maximum concentration from 100 ppb to 80 ppb of DBPs. Addition of ammonia at the end of the treatment has been effective in controlling the formation of THM constituents in the distribution system. Since 2005, the water is chlorinated after the two degassifiers (aeration towers) and ammonia is added to reduce the free chlorine levels to reduce THM formation. Presently, the EWTP is

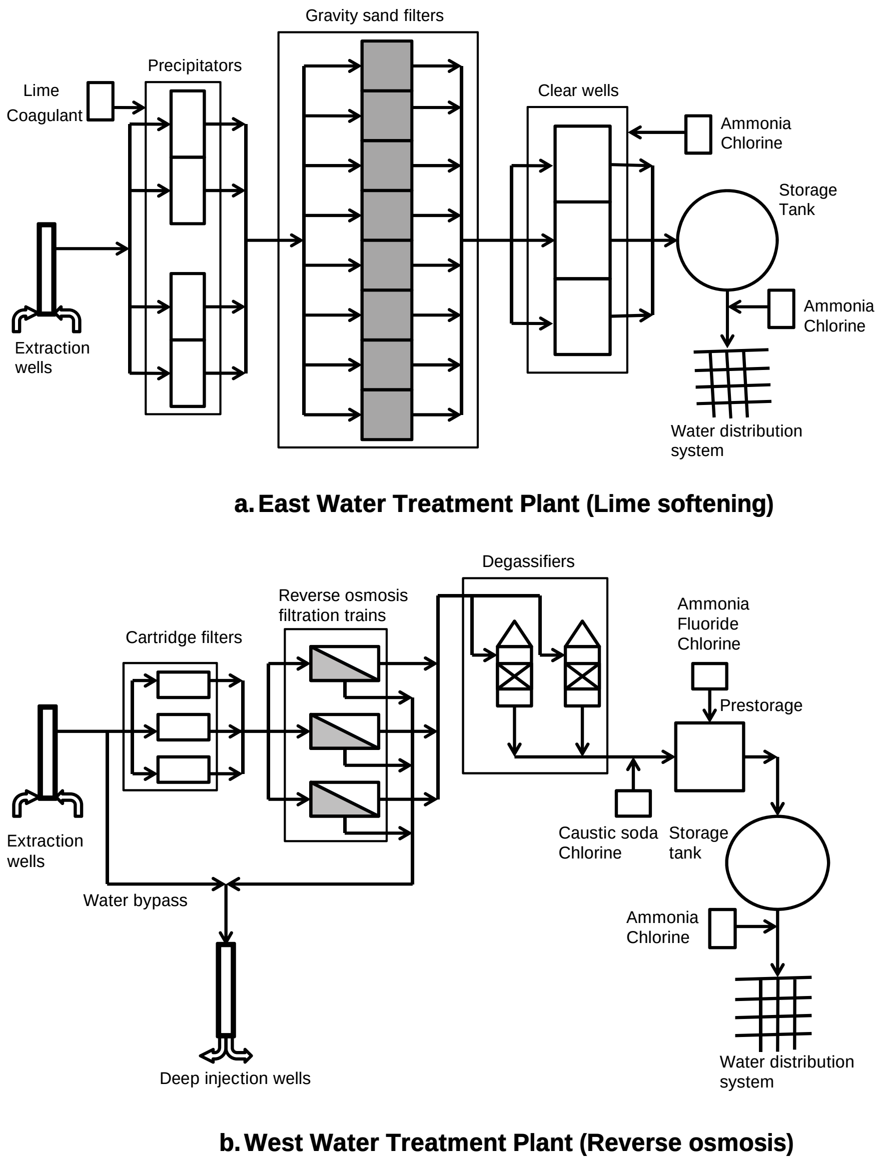


Fig. 1. Flow diagrams of East and West water treatment plants. (a) East Water Treatment Plant (Lime softening). (b) West Water Treatment Plant (Reverse osmosis).

capable of producing 4 MGD (15,000 $m^3 d^{-1}$) of drinking water to the eastern portion of Miramar including some parts of the west side of Miramar, which are close to the blending zone where water from both plants are mixed.

The West Water Treatment Plant (WWTP) provides 7 MGD (26,500 $m^3 d^{-1}$) of water treated by reverse osmosis. The plant was initially constructed with a capacity of 4.4 MGD (16,700 $m^3 d^{-1}$) and expanded to 16 MGD (60,000 $m^3 d^{-1}$) due to significant growth in the western part of the City during the 1980s. Water from the groundwater wells passes through the cartridge filters before the membrane filtration (Fig. 1b). Prior the membrane filtration, sulfuric acid and an antiscalant (to increase solubility and to keep solids in suspension) are added to prevent clogging or scaling of the membranes. The concentrate, which is about 20% of the total production, is disposed by injection wells to the boulder zone which is about 3080 feet (940 m) below the ground surface. Hydrogen sulfide and carbon dioxide are removed by aeration. Sodium hydroxide is added for alkalinity adjustment to prevent corrosion of the pipes. Fluoride is added for prevention of tooth decay and sodium hypochlorite is used for disinfection.

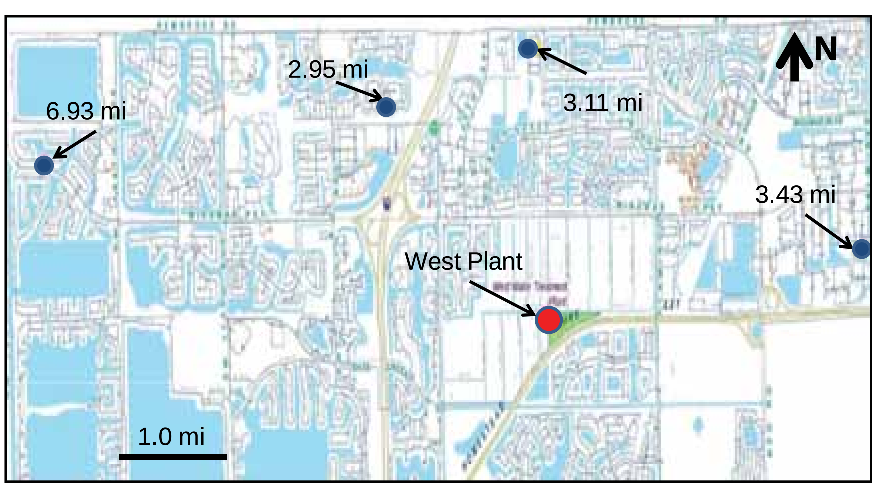
2.2. Sampling locations

The locations of the DBP compliance monitoring sites were determined based on the population served. Ten sampling locations were selected for monitoring THM levels based on distance from the treatment plants as shown in Fig. 2. Five of the sites were served by the East plant (at 0, 0.5, 1.3, 1.4, 2.5 miles) and five were served by the West plant (at 0, 2.95, 3.11, 3.43, 6.93 miles). The sampling locations included both residential and commercial areas. The grab samples were collected four times a year (similar to system-wide the quarterly DPB sampling program). Cul de sac samples were collected from 27 locations which were identified as points in the distribution system where the piping lay out indicated dead ends which may have relatively longer water age due to fewer number of residences. Of the 27 samples, 25 were served by the east plant (with older distribution system) and two were served by the west plant (newer section of the city). The newer part of the city, which is served by the west plant, had fewer cul de sac locations in piping layout with easy access for sampling.

2.3. Sampling procedure

Water samples for THM analyses were collected in 40 mL bottles and capped with PTFE coated septa. Samples were preserved with sodium thiosulfate (for chlorine neutralization) and stored at 4 °C during transportation. Before collecting the water samples, water was run for 1 min as a standard procedure for this program to ensure that the water collected was representative of the dead end street but not specific to the one particular residence (which may affect water quality due to the piping installed by the owner). Samples were analyzed by EPA 524.1 method.

a. East Water Treatment Plant



b. West Water Treatment Plant

Fig. 2. Sampling locations in areas served by East and West water treatment plants.

3. Results

Water quality in the City of Miramar distribution system was monitored for THM levels in the areas served by the EWTP which uses lime softening and the WWTP which uses reverse osmosis processes. Field monitoring locations were selected to investigate the significance of distance from the water plant and at cul de sacs. Fig. 3 presents the THM levels in areas served by the East (lime softening) and West (reverse osmosis) water treatment plants over time. The THM levels from the cul de sac sampling are also indicated on the graphs. For the East (lime softening) plant, a small increase in THM levels was observed over time. For the West (reverse osmosis) plant, after the start up period of the membrane systems, THM levels were consistently low during the 2004–2008 period. The higher THM levels observed during 2002 correspond to the operational adjustments in chemical use and operating conditions of the osmosis filters. After 2008, a steady increase in THM levels was observed over time due to aging and fouling of the membranes which had been in service for over 7 years. During the first four years (2003–2007) when the membranes were new, the THM levels were significantly low as shown in Fig. 3.

Fig. 4 compares the system wide THM levels with those observed at the cul de sac locations in relation to chlorine residual. For areas served by the East plant

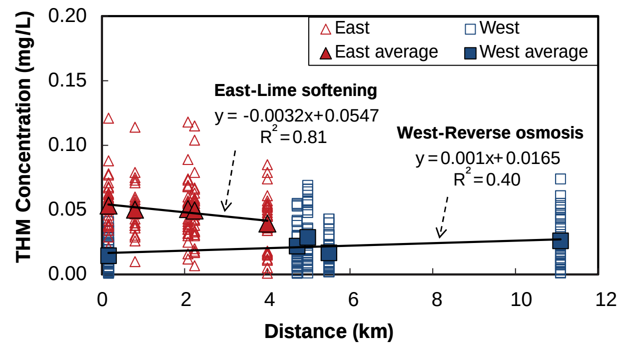


Fig. 5. Variation of THM concentration with distance in the areas served by East and West water treatment plants in quarterly samples collected during 2001–2010.

(lime softening), the THM levels at cul de sacs were consistently higher than levels observed system wide. For the areas served by the West plant (reverse osmosis), the THM levels at cul de sacs were similar to the levels observed system wide. Also, for the areas served the West plant (reverse osmosis), the THM and chlorine residual concentrations were significantly lower and had lower variation in comparison to those areas served by the East plant (lime softening).

Fig. 5 compares the variation of THM levels with distance for the East (lime softening) and West (reverse osmosis) plants. The field monitoring data showed an

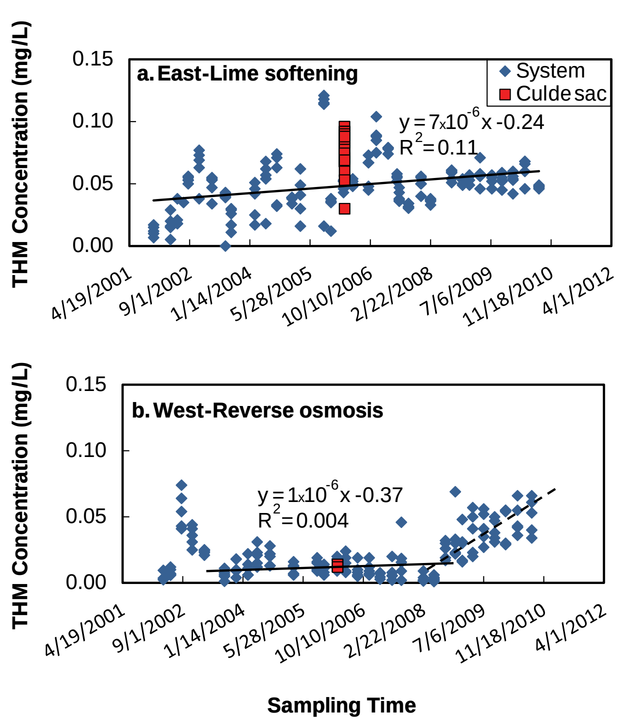


Fig. 3. Variation of THM concentration over time in areas served by East and West water treatment plants. Cul de sacs were sampled once during March 2006.

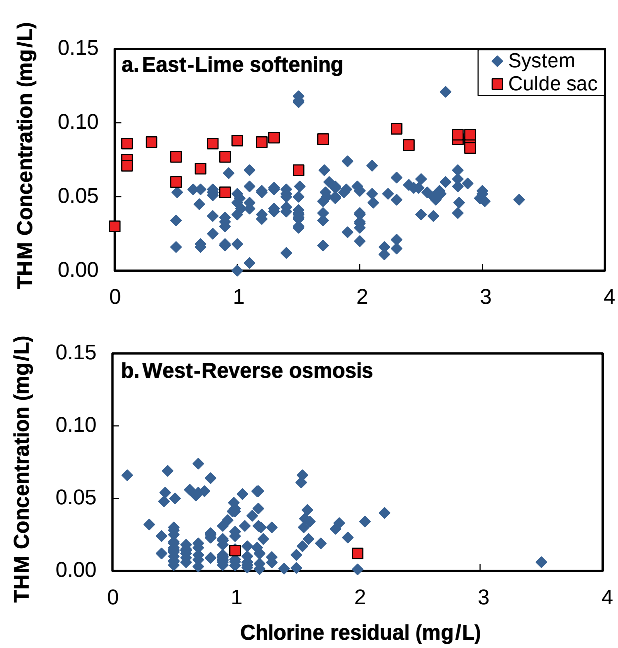


Fig. 4. Variation of THM concentration with chlorine residual levels in the areas served by East and West water treatment plants. Cul de sacs were sampled once during March 2006, system wide monitoring data correspond to quarterly samples collected during 2001–2010.

increasing trend for THM levels with distance for the areas served by the West (reverse osmosis) plant. The THM levels at the areas served by the East (lime softening) plant were higher and did not show significant variability with distance. It should be noted that the most distant point served by the East plant and the most distant point served by the West plant are close to the blending point from both plants.4. Conclusions

Effectiveness of lime softening and reverse osmosis processes were compared in terms of formation of THMs in the distribution system with distance and at cul de sac locations. The water treated by lime softening showed significantly higher levels of THMs in comparison to the water treated by reverse osmosis process. However, with the aging of the reverse osmosis membranes, the THM levels in the water distribution system were similar to that treated by the lime softening process. The THM levels at the cul de sacs in areas receiving water treated by lime softening were significantly higher in comparison to the system wide water quality. The effective life of reverse osmosis membranes is significantly reduced if they are used for removal of dissolved organic compounds, hence prevention of THM formation. The membranes should be replaced every 4–5 years under the current operating conditions. The THM levels at the cul de sacs receiving water treated by reverse osmosis were similar to the system wide water quality. Distance from the treatment plant was not a significant factor for THM formation in the distribution system.

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