Drinking water: the problem of chlorinous odors

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Chlorinous off-flavours in drinking water are a leading cause of complaints to Australian water utilities, and other utilities worldwide. The occurrence and causes of chlorinous odors in drinking water were investigated with the use of an odor panel, trained using a modified flavour profile analysis (FPA) technique. A new system for classifying water types according to the causes of chlorinous odors was developed in order to enable improved management strategies for the reduction of these off-flavours. Waters of ‘Type 1’ exhibit a chlorinous odor only when the free chlorine equivalent concentration is equal to or above the odor threshold concentration (OTC) for free chlorine. Waters exhibiting a chlorinous odor both above and below the OTC of free chlorine are designated ‘Type 2’. ‘Type 3’ waters are those in which the possible presence of a chlorinous odor is masked by another odor. Although causative compounds of the chlorinous off-flavours were not determined, bromine was proposed to play an important role in distribution systems where source waters have high concentrations of bromide that may not be removed by the available treatment processes. Management strategies for improvements in aesthetic water quality for each water type were proposed.

Keywords: Drinking water, off-flavours, chlorine, bromine, natural organic matter, water treatment
INTRODUCTION

Chlorinous off-flavours in drinking water are a leading cause of taste and odor complaints to water utilities in Australia (Joll et al., 2007), and are also commonly reported worldwide (Mackey et al., 2004a). Aesthetic quality of drinking water is usually the only measure of quality available to most consumers, and is therefore the basis by which consumers judge the safety of drinking water (McGuire, 1995). The end result may be reduced confidence in water utilities, increased consumption of bottled water (McGuire, 1995), and a shift towards point of use or point of entry treatment devices (Mackey et al., 2004a).

Despite obvious concern by water authorities (Khiari et al., 1999; Welte and Montiel, 1999; Marchesan and Morran, 2004), identification of the causes of chlorinous off-flavours is often difficult. Chlorinous off-flavours can be transient, and may diminish by the time a field officer can arrive to inspect the problem (Willmore, 2005). In addition, consumers often do not accurately identify chlorinous off-flavours (Mackey et al., 2004b). The presence of any objectionable odor may be misidentified as chlorinous because of widespread awareness of chlorine as a key drinking water chemical (Mackey et al., 2004b).

Many Australian treated waters, particularly Western Australian waters, require relatively high chlorine doses (up to 7 mg/L for pre-chlorination and up to 4 mg/L for chlorination post-treatment) due to high levels of dissolved organic carbon (DOC) remaining after treatment. Additionally, some above ground pipelines are exposed to frequent high temperatures, causing greater chlorine decay rates (Joll et al., 2007). Elevated chlorine doses are essential to ensure adequate disinfection throughout the distribution system, but can make management of chlorinous off-flavour incidents difficult.
A number of chlorinous off-flavour complaints are received each year by the Water Corporation of Western Australia, the water utility supplying the majority of drinking water in the state of Western Australia. Complaints are typically widespread across the Metropolitan Region of Perth, the capital city of Western Australia. In the Perth Metropolitan Region, approximately 50-60% of the distributed drinking water is derived from groundwater extraction, 15-20% from seawater desalination (introduced in November 2006), and the remaining 20-35% from surface water storages located in the Darling Range (Water Corporation, 2009). Perth’s groundwater for drinking purposes is obtained from the Jandakot Mound and the Gnangara Groundwater System. The latter system includes a surficial aquifer (the Gnangara Mound), the underlying semi-confined Mirrabooka aquifer, and the deeper confined Leederville and Yarragadee aquifers. While the local surface water typically requires minimal treatment, the quality of the groundwater varies widely and groundwater sources commonly require a number of treatment steps to reduce the concentrations of DOC, H2S, NH3 and iron, and to reduce colour and turbidity.

Consumer complaints of chlorinous off-flavours are a serious problem for many utilities that use chlorine-based disinfectants worldwide, since these taints adversely affect consumer perceptions of water safety and quality. It is therefore of significant interest to further investigate chlorinous off-flavours. The aims of this study were to identify and classify the causes of chlorinous off-flavours, using the Perth distribution system. Since elevated bromide concentrations occur frequently in southern Australian source waters and since brominated compounds are generally more organoleptically potent than their chlorinated analogues (Acero et al., 2005), the role of bromide in chlorinous off-flavours was also investigated. This is the first study of the role of bromide in the formation of chlorinous off-flavours in drinking water. A new system for classifying water types
according to the causes of chlorinous odors was proposed. Improved water quality management practices to reduce these off-flavours in distributed waters were developed.

MATERIALS AND METHODS

Preparation of glassware

All glassware was carefully prepared to remove odors and contaminants. Preparation included final rinsing with ultrapure water (Milli-Q) several times, and annealing the glassware in an oven set at 550°C overnight, with the annealed glassware being stored in a room without background odor. Just prior to use, glassware was rinsed at least three times with sample water.

Sample sites and collection

Samples were collected from drinking water treatment plant outlets in amber bottles, filled to the top to minimise headspace, and immediately transported in a cooler to the laboratory. The primary samples were taken from two surface water treatment plant outlets (SW 1 and SW 2), and six groundwater treatment plant outlets (GW 1, GW 2, GW 3, GW 4, GW 5, and GW 6) in the Perth Metropolitan Region, forming the foundational study sites for this research.

The water quality of the surface water sources is relatively good, with no treatment other than disinfection and fluoridation currently employed (Allpike, 2008). The groundwater treatment plants source groundwater from a number of different aquifers in the Gnangara Groundwater System, as shown in Table 1.

The water treatment processes employed at the different groundwater treatment plants were as follows: GW 1 (GW1 extracts water from a limestone formation rather than
interbedded sandstone, siltstone and shale (Salama, 2005)): aeration, lime softening, pH adjustment, filtration, chlorination and fluoridation; GW 2: pre-chlorination and aeration, enhanced alum coagulation, rapid sand filtration, lime softening, chlorination and fluoridation; GW 3: aeration, pre-chlorination, a magnetic ion exchange (MIEX®) resin process, alum coagulation, chlorination for manganese removal and filtration, before final chlorination and fluoridation; GW 4: pre-chlorination, coagulation, rapid sand filtration, post-chlorination and fluoridation; GW 5: aeration, pre-chlorination, alum coagulation, rapid sand filtration, final chlorination and fluoridation; GW 6: chlorination and fluoridation only.

Additional study sites (SW 3, GW 7, GW 8 and GW 9) were included to provide a larger sample size for examination of the role of bromide in the causes of chlorinous odors in treatment plant outlet waters. SW 3 was located in tropical North Western Australia and GW 7, GW 8 and GW 9 were in the Perth Metropolitan Region. The treatment processes were as follows: SW 3: polyaluminium chloride coagulation, membrane filtration, chlorination and fluoridation; GW 9: chlorination and fluoridation. GW 7 and GW 8 were storage supplies in Perth’s Integrated Water Supply System.

**Chlorine concentrations of treatment plant outlet water samples**

Treatment plant outlet water samples were temperature controlled (25°C) upon arrival in the laboratory. Free and total chlorine equivalent concentrations in the samples were measured immediately, and periodically over time until the free and total chlorine equivalent concentrations were not detectable (< 0.02 mg/L). Free and total chlorine equivalent concentrations were measured in duplicate using a DPD-based method with a pocket colorimeter (HACH, Loveland, CO, USA).

**Odor assessment of treatment plant outlet water samples**
After temperature-control (25°C) for half an hour, the treatment plant outlet samples were poured into wide-necked conical flasks (250 mL) fitted with watch glass lids just prior to assessment of odors by the odor panel, according to the method described by McDonald and co-workers (McDonald et al., 2009). All odors, including chlorinous odors, were recorded by the panellists. Previously, the OTC for free chlorine was found to be 0.1 ± 0.05 mg/L by this odor panel (McDonald et al., 2009). Further odor panel events were conducted on the equilibrated water samples when the free and total chlorine equivalent concentrations were above and below the OTC for free chlorine.

**Organic and inorganic water quality parameters**

The free chlorine in a subsample of each water sample was quenched by the addition of aqueous sodium sulphite solution (4.25 mL; 12 g/L) and the quenched samples were analysed by a commercial laboratory (SGS Australia Pty. Ltd.) for a number of water quality parameters (Table 2). Bromide was analysed in our laboratory by ion chromatography with UV detection (Dionex ICS90; Dionex Corporation, Sunnyvale, CA) using a Dionex IonPac® AS23 ion exchange column (4 x 250 mm) and a carbonate eluent (1.0 mM NaHCO₃ and 10.2 mM NaCO₃).

**RESULTS AND DISCUSSION**

Water samples were collected from eight treatment plant outlets in the Perth Metropolitan Region. These samples were analysed for general water quality parameters and the chlorine concentrations and odor characteristics were monitored over time (25°C).

**Water quality characteristics of treatment plant outlet samples**
Typically, surface water samples had lower alkalinity, total alkalinity and hardness than the water exiting the groundwater treatment plants (Table 2), due to the greater exposure of the groundwater to carbonate-containing rocks.

Groundwater samples generally had higher chloride and bromide concentrations than the surface water samples, except for GW 5 (chloride 42 mg/L; bromide 0.18 mg/L) where the lower bromide and chloride content was consistent with its up-gradient location in the Gnangara Mound (Davidson, 1995). The highest bromide concentrations were found in GW 1 and GW 3 (both 0.43 mg/L).

The bromide concentrations in these water samples would be considered as moderate to high in comparison to those in previous reports for natural waters used for drinking water (e.g. < 0.25 – 0.54 mg/L) (Boyer and Singer, 2005; Singer et al., 2007), with moderate concentrations reported as around 0.11 mg/L (Ates et al., 2007), and very high concentrations around 0.70 mg/L (Hansson et al., 1987). The current water samples were quenched with a reducing agent to reconvert any aqueous bromine (HOBr and OBr⁻), which would have formed from reaction of naturally occurring bromide with chlorine, to bromide. Some of this bromine may have already reacted with other species, e.g. DOC, to produce brominated disinfection by-products (DBPs). The bromide concentrations in the source waters and treated waters prior to addition of chlorine may therefore have been higher than those measured in the quenched treatment plant outlet waters. The bromide concentrations in GW 1, GW 2, GW 3, and GW 6 were around 0.4 mg/L or greater, and could be considered as moderately high in the worldwide perspective.

DOC concentrations were relatively high for all treatment plant outlet waters, ranging from 1.8 mg/L for GW 4 to as high as 3.6 mg/L for GW 5. With the exception of GW 1 and GW
6, the groundwater treatment plants had a DOC removal step. The relatively high DOC concentrations in the treatment plant outlet waters indicate that removal of DOC is difficult and that there remains a refractory component of the DOC which is not well-removed.

**Odor assessment and chlorine concentrations of treatment plant outlet samples**

Free and total chlorine equivalent concentrations of the treatment plant outlet samples were measured over time (Figure 1). Odors were assessed by the odor panel, at least once when the free chlorine equivalent concentration was above the free chlorine OTC, and at least once when the free chlorine equivalent concentration was below the OTC for free chlorine, as shown in Figure 1. The odor panel assessments (events) were plotted as the corresponding free chlorine equivalent concentration measured at the time of the event.

The odor panel detected a chlorinous odor as the predominant odor in SW 1, SW 2, GW 1, GW 3, GW 4, GW 5 and GW 6 samples when the free chlorine equivalent concentration was at or above the OTC for free chlorine, but not below the OTC for free chlorine. GW 3 had different odor characteristics to the other four samples (SW 1, SW2, GW 4 and GW 5), exhibiting an additional odor, which will be discussed later. Samples SW 1, SW 2, GW 4 and GW 5 were therefore classified as ‘Type 1’, where a chlorinous odor is only detected when the free chlorine equivalent concentration is at or above the OTC for free chlorine and where the chlorinous odor is therefore likely due to the presence of free chlorine.

Not all water treatment plant outlet samples behaved in this manner: for samples GW 1 and GW 6, a chlorinous odor was detected not only when the free chlorine equivalent concentration was above the OTC for free chlorine, but also consistently when the free chlorine equivalent residual was lower than the OTC for free chlorine, and even when
there was no detectable free chlorine equivalent residual (limit of detection of 0.02 mg/L).

For GW 1, there was a chlorinous odor detected by the panel when neither free nor total chlorine equivalent residual were detectable. These samples were classified as 'Type 2'.

The off-flavour associated with free chlorine is due to the species, hypochlorous acid (HOCl) and the hypochlorite ion (OCl\textsuperscript{-}) (Krasner and Barrett, 1984). Studies have found that the aroma threshold value for OCl\textsuperscript{-} is higher than for HOCl, indicating that a lower pH could result in a more easily detected chlorinous odor (Krasner and Barrett, 1984). The major species present depends upon pH, with the pK\textsubscript{a} of HOCl being 7.53. The Australian Drinking Water Guidelines specify a pH of finished water between 6.5 and 8.5 (ADWG, 2004). At pH 6, 95% of the hypochlorite will be in the HOCl form and, at pH 9, the predominant species present will be OCl\textsuperscript{-} (Clark and Sivaganesan, 2002). Type 1 water samples exhibited a range of pH (Table 2): SW 1 (pH 6.7), SW 2 (pH 7.5), GW 3 (pH 8.7), GW 4 (7.5) and GW 5 (pH 7.8), indicating that some samples contained predominantly hypochlorous acid and some samples predominantly hypochlorite, but presumably the lower the pH, the more easily detected the odor due to chlorine.

The presence of a chlorinous odor without the presence of any free chlorine equivalent concentration suggest that the odor is due to compounds that are not free chlorine nor other compounds capable of the DPD oxidation reaction required for the measurement of free chlorine. Most taste and odor problems not due to excess chlorine are thought to be due to compounds formed upon the reaction of the oxidizing disinfectant with natural organic matter, i.e. DBPs (Freuze et al., 2004).

In the Type 2 waters, when there was no free chlorine equivalent residual remaining, the chlorinous odor was likely due to one or more DBPs. When the free chlorine equivalent
concentration was present but below the free chlorine OTC, the chlorinous odor may have been due to these one or more DBPs and, possibly, oxidants other than chlorine. When the free chlorine equivalent concentration was above the free chlorine OTC, the chlorinous odor may have been due to some or all of these factors, as well as free chlorine itself.

Reports of chlorinous off-flavours due to compounds other than free chlorine have previously been reported in South Australian (Morran and Marchesan, 2004) and French (Welte and Montiel, 1999) distribution systems. Morran and Marchesan (2004) suggested that the chlorinous off-flavour was due to combined chlorine compounds, such as complex chloramines or other chlorinated compounds. Welte and Montiel (1999) proposed that the cause of the chlorinous off-flavour may have been trichloramine which formed during chlorination of some organic nitrogen compounds. The taste and odor episode in France (Welte and Montiel, 1999) provoked further research into the possible origins of chlorinous off-flavours (Freuze et al., 2004; Freuze et al., 2005) where N-chloroaldimines were found to form from reactions between chlorine and amino acids, and to exhibit chlorinous odors, with OTCs as low as 1 µg/L. Earlier studies also linked chlorinous odors to the presence of chloramines formed during chlorination of amino acids and peptides (Bruchet et al., 1992).

Other potential chlorinous off-flavour compounds include monochloramine (Krasner and Barrett, 1984; Piriou and Perelle, 1999), dichloramine (Krasner and Barrett, 1984), aldehydes (Froese et al., 1999), and bromine (McDonald et al., 2009). Potentially, bromamines could also impart a chlorinous odor, however, the OTCs or descriptors for bromamines have not previously been reported.

In addition, untrained panellists (the majority of drinking water consumers) are not always able to determine the difference between chlorinous, medicinal, and chemical odors (Mackey et al., 2004b). ‘Chlorinous’ off-flavours may therefore also include other
compounds found in drinking water. A range of compounds reported to be present in water and associated with having a chlorinous off-flavour by consumers (but not typically described as such by trained panellists) were reported by Mackey and co-workers (2004b), and broadly include trihalomethanes (THMs), halophenols, and miscellaneous phenol-based compounds. In the current study, it is unlikely that the chlorinous odors in Type 2 waters were due to combined chlorine compounds such as chloramines. Some Type 1 waters had higher ammonia or Total KN concentrations than Type 2 water (Table 2), and it would be expected that these waters would contain higher concentrations of chloramines than the Type 2 waters, but they did not exhibit chlorinous odors. There was no observed link between ammonia or total Kjeldahl nitrogen (TKN) concentrations and chlorinous odors, or indeed, between combined chlorine and chlorinous odors. Additionally, at least one of the study sites (GW 1) exhibited a distinct and persistent chlorinous odor when total chlorine residual was not detectable. Other odorous compounds were therefore indicated, although the odorous compounds may well be organic bromamines (or chloramines) that are present below the detectable limit for total chlorine.

The GW 2 sample exhibited different odor characteristics to the other samples (Figure 1). GW 2 did not exhibit a chlorinous odor even when the free chlorine equivalent concentration was above the OTC for free chlorine. At all odor panel events, this sample was described as having a strong ‘sulphurous’ odor. This odor presumably masked the odor of chlorine when the free chlorine equivalent concentration was above the OTC of free chlorine. Groundwater from the Gnangara Mound contains significant concentrations of sulphide which is oxidised using aeration and pre-chlorination during treatment. Oxidation of sulphides using this method is often incomplete and the partially oxidised sulphur compounds that are formed may impart the sulphurous odor (Heitz et al., 2000; Heitz, 2002). Up to ~100 µg/L residual partially oxidised sulphur compounds remain after
treatment of these sulfidic groundwaters (Wilmot and Wajon, 1997). It has been suggested that this fraction of sulphur would be limited to compounds such as elemental sulphur sols, possibly associated with organic matter, refractory organosulphur compounds, or particulate iron-sulphides (Heitz, 2002). Possible sources of sulphurous odors in drinking water may be due to one or more heterocyclic organosulphur compounds of the formula \(C_3H_6S_3, C_4H_8S_2, \) and \(C_5H_{10}S_2\) (dithiolanes and trithiolanes) (Heitz, 2002). Dithiolanes and trithiolanes are known to have strong sulphurous or sulfidic odors (Fors, 1983). However, it was not possible to directly attribute the sulphurous odor in the water samples in this study to any of these substances.

If any chlorinous odors were present when the free chlorine equivalent concentration was below the free chlorine OTC, they would also have been masked by this odor. This sample was therefore designated as ‘Type 3’, where chlorinous odors that may be present are masked by another stronger odor. The concept of masking is well known, e.g. for free chlorine masking earthy and musty odors in drinking waters (Suffet et al., 1995), but this is the first report of a sulphurous odor masking a chlorinous odor in a drinking water.

The odor panellists (60%) also detected a sulphurous odor in the GW 3 sample when the free chlorine equivalent concentration was below the OTC for free chlorine. The sulphurous odor was present (detected by 20% of panellists), but not strong enough to mask the chlorinous odor, when the free chlorine equivalent concentration was above the OTC of free chlorine, but became important when the free chlorine equivalent concentrations were low, masking any possible chlorinous off-flavours present. This water was therefore also designated as being of Type 3, as it contained an additional odor that could mask chlorinous odors, albeit over a lower chlorine equivalent concentration range.
Role of bromide in the formation of chlorinous odors

Bromide occurs naturally in many drinking water sources, with concentrations commonly ranging from around 0.05 to 0.80 mg/L in Western Australian source waters (Heitz et al., 2004), but can reach up to 2.8 mg/L and higher if the water is affected by saltwater intrusion or other phenomena (Gruchlik et al., 2011). Bromide is difficult to remove with conventional water treatment practices and is readily oxidised by chlorine during water treatment to form bromine (Westerhoff et al., 2004). This has a number of implications for studies of chlorinous odors. First, during the analysis of chlorine concentrations, the bromine can also react with the DPD reagent and be measured as its free chlorine equivalent concentration, and secondly, the presence of bromine must be considered when assessing off-flavours, as bromine has been described as having a chlorinous odor (McDonald et al., 2009).

The composition of the initial free chlorine equivalent concentrations in a series of treated water samples, including the treatment plant outlet waters and four additional water samples (SW 3, GW 7, GW 8, GW 9), is given in Table 3. Since chlorine was present in excess in these samples, and oxidation of bromide by chlorine is relatively rapid ($k_{Br^- + HOCl} \rightarrow HOBr + Cl^- = 1.55 \times 10^3 \text{ M s}^{-1} \text{s}^{-1}$) (Kumar and Margerum, 1987), it can be assumed that all of the bromide measured in the quenched samples would have been present as bromine in the samples collected. In this case, up to 34% of the free chlorine equivalent concentrations would have been due to bromine in these samples (Table 3). It is therefore likely that the measured chlorine residual in many parts of the distribution system comprises at least some portion of bromine. This understanding of the importance of bromine as a residual disinfectant in distribution systems where the source water is high in bromide concentration and the treatment processes do not significantly remove bromide, fills a key knowledge gap for water utilities. McDonald and co-workers (2009) determined
the OTC for bromine to be 0.04 mg/L free chlorine equivalents (odor described as chlorinous), while the free chlorine OTC was 0.1 mg/L. Therefore, at free chlorine equivalent concentrations below 0.1 and above 0.04 mg/L, a chlorinous odor cannot be due to the presence of chlorine but could well be due to the presence of bromine.

For Type 1 and 2 waters, the relationships between water type and bromide concentration in the quenched samples is shown in Figure 2. A significant correlation was observed between bromide concentration and water type (p = 0.0095, Spearman’s rank correlation). The probability of drinking water exhibiting a chlorinous odor when the free chlorine equivalent concentration is below the OTC for free chlorine appeared to increase with higher bromide concentrations in the quenched samples.

While bromine itself may be contributing to chlorinous odors at low equivalent free chlorine concentration (0.04 – 0.1 mg/L), in the cases of GW1 and GW6, chlorinous odors were detected at concentrations even lower than the OTC of bromine. These samples exhibited chlorinous odors when the free chlorine equivalent concentration was below the method detection limit of 0.02 mg/L, well below the published OTC of bromine. In these cases, other compounds must have contributed to the odor, and in light of the relationship between bromide and Type 2 waters, it is probable that these compounds are bromine-containing, either brominated DBPs or inorganic bromamines. The speciation of DBPs will be influenced by the bromide ion concentration in the water source, since bromine can react with NOM preferentially to chlorine to produce more brominated, rather than chlorinated, DBPs (Clark et al., 2001).

Implications for drinking water management strategies
For Type 1 sites, chlorinous off-flavour complaints are likely to be caused by the free chlorine equivalent concentration, comprised predominantly of free chlorine, and will most likely occur closer to the treatment plant. Management options for these waters could include a reduction in chlorine dose, while still ensuring sufficient residual throughout the distribution system. The ability to do this would depend upon the chlorine demand and residence time of the water in the distribution system.

In these studies, high concentrations of bromine (> 0.3 mg/L) appeared to have a large influence on the formation of the chlorinous off-flavours. Management strategies to improve the aesthetic quality of Type 2 waters would include reduction of bromide concentration during the treatment process. Bromide removal would aid in the reduction of chlorinous off-flavours due solely to bromine (measured as a chlorine equivalent), and also in reduction of the formation of any other odorous, brominated DBPs that could contribute to chlorinous off-flavours. For Type 3 waters, off-flavour issues are significant and removal of groundwater-derived sulphurous compounds, or more complete oxidation of these compounds to sulphate, in water treatment processes would improve the aesthetic water quality.

Currently, there are no economically feasible methods to remove bromide from source waters such as those in the current study, where high concentrations of bromide are accompanied by high concentrations of NOM. New, cost-effective methods for selective removal of bromide from drinking waters are our current focus and may provide significant benefits in terms of mitigation of chlorinous off-flavours.

Conclusions
A new system for classifying water types according to the cause of chlorinous off-flavours was developed. Type 1 waters exhibited a chlorinous odor only when the free chlorine equivalent concentration was equal to or above the OTC for free chlorine. Type 2 waters exhibited a chlorinous odor both above and below the OTC for free chlorine. Type 3 waters had the presence of another odor that masked any chlorinous off-flavours.

Up to 34% of the free chlorine equivalent concentration in these samples was found to be due to bromine. Water Type classifications were found to be related to the concentration of bromide in the quenched samples. Bromine was proposed to play an important role in disinfectant residual and chlorinous odors in waters in distribution systems where source waters have high concentrations of bromide which is not removed by the available treatment processes.

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Table 1. Water sources for the groundwater treatment plants.

<table>
<thead>
<tr>
<th>Groundwater Treatment Plant Sample</th>
<th>Water Source</th>
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<td>Superficial Aquifer</td>
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<td>Leederville Aquifer</td>
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<tr>
<td></td>
<td>Yarragadee Aquifer</td>
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</tr>
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<td>GW 2</td>
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<td>GW 5</td>
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<tr>
<td>GW 6</td>
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**Table 2.** Water quality parameters of treatment plant outlet samples.

<table>
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<th>Water Sample</th>
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<tbody>
<tr>
<td></td>
<td>SW 1</td>
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<tr>
<td>Alkalinity as HCO_3 (mg/L)</td>
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<td>Bromide (mg/L)</td>
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<td>Chloride (mg/L)</td>
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<td>Dissolved organic carbon (mg C/L)</td>
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<td>Iron (mg/L)</td>
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<td>Total alkalinity as CaCO_3 (mg/L)</td>
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<tr>
<td>Ammonia as nitrogen (mg/L)</td>
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<td>Total Kjeldahl nitrogen (TKN) (mg/L)</td>
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<tr>
<td>^Free chlorine equivalent concentration (mg/L)</td>
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<tr>
<td>^Total chlorine equivalent concentration (mg/L)</td>
<td>1.12</td>
</tr>
</tbody>
</table>

nd = no data because it was not measured.
$^a$Measured at 1.5 hours after sampling.