



**RMP**  
REGIONAL MONITORING  
PROGRAM FOR WATER QUALITY  
IN SAN FRANCISCO BAY

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# Investigation of quaternary ammonium compounds (QACs) in wastewater effluent, influent, biosolids, and environmental matrices in San Francisco Bay

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# **Investigation of quaternary ammonium compounds (QACs) in wastewater effluent, influent, biosolids and environmental matrices in San Francisco Bay**

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## Executive Summary

Quaternary ammonium compounds (QACs) are surfactants widely used in a variety of consumer products, particularly as antimicrobials. The COVID-19 pandemic has increased use of products containing QACs. This is of concern because QACs can be toxic to aquatic life at low concentrations. This study was undertaken to evaluate the concentrations of 21 QACs in municipal wastewater influent, effluent, and biosolids from three treatment plants in the San Francisco Bay Area. The QACs detected in wastewater influent in the highest concentrations are those commonly used as antimicrobials in disinfectant products, indicating that disinfectants are likely a large source of QACs to wastewater. While wastewater treatment removed QACs in the aqueous phase, as evidenced by much lower concentrations in effluents than influents, total levels present in treated effluent were still on the order of hundreds of ng/L to low  $\mu\text{g/L}$ . High amounts of QACs were found sorbed to biosolids, which could provide another environmental release route.

QACs were also observed in San Francisco Bay water, sediment, and urban stormwater runoff samples collected as part of ongoing monitoring by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). Wastewater effluents and stormwater runoff are both pathways for QACs to enter San Francisco Bay. We classify QACs as a Possible Concern for the Bay in the RMP's tiered risk-based framework for emerging contaminants, based primarily on the limited number of ambient Bay samples analyzed, and recommend additional screening of Bay water in the future.

## Introduction

Quaternary ammonium compounds, first used in the 1930s as surfactants and disinfectants, are found in many consumer, agricultural, healthcare and industrial products including fabric softeners, personal care products, disinfectants, biocides, sanitizers, and emulsifiers.<sup>1-4</sup> QACs are generally a class of chemicals that have a positively charged nitrogen atom with two methyl groups, a long alkyl chain of varying length, and a fourth side chain that varies in structure. Several within this class are designated as high production volume chemicals, with over one million pounds manufactured or imported annually.<sup>5-7</sup> Estimated reported production values show that up to 50 million pounds of certain QACs are produced per year dating back to 2012.<sup>8</sup> Due to the COVID-19 pandemic, use of QAC containing products has increased, and over 50% of the disinfectants on EPA list N: *Disinfectants for Use against SARS-CoV-2* contain QACs as an active ingredient.<sup>7,9</sup> Of those 216 products, most contain benzylalkyldimethylammonium compounds (BACs) and/or dialkyldimethylammonium compounds (DADMACs) (93.5% and 49.5%, respectively). Ethylbenzylalkyldimethylammonium compounds (EtBACs) are present in 34% of the disinfectants. Chain lengths of QACs used in disinfectants include C<sub>8</sub>- to C<sub>18</sub>-BACs (with C<sub>14</sub> usually having the highest percentage in common formulations), C<sub>12</sub>- and C<sub>14</sub>-EtBACs and C<sub>8</sub>-, C<sub>8/10</sub>-, and C<sub>10</sub>-DADMACs. In contrast, alkyltrimethylammonium compounds (ATMACs; C<sub>8</sub> and longer) are used in fabric softeners and hair products.

Most QACs are both water soluble and strongly sorb to solids and surfaces.<sup>10,11</sup> QACs have been previously detected in wastewater influent and effluent, surface waters, sediments and biosolids.<sup>10,12-17</sup> Approximately 75% of QACs used worldwide annually end up in

wastewater treatment systems, where 90% or greater are removed from the liquid phase mainly during activated sludge treatment.<sup>1,11,18,19</sup> Because QACs are highly sorptive, the main removal mechanism in wastewater treatment is sorption to activated sludge, but aerobic degradation also occurs.<sup>11,19</sup> While a large percentage of QACs are removed during treatment, these compounds are produced and used in such high volumes that the amount being released to the environment is still significant.<sup>15</sup> In addition, QACs may be discharged to the environment through land application of biosolids or from their use as surfactants in other commercial products, such as pesticide formulations.

In disinfectant products, QACs are present at high levels to inactivate viruses and kill bacteria. In the environment, however, they are typically present at much lower, sub-lethal concentrations. Thus, bacteria may not be killed, but could be stressed and adapt to the QACs. Indeed, research has shown that QACs may contribute to the global antibiotic resistance problem.<sup>20–24</sup> A 2022 study investigated the induction of antibiotic resistance by C<sub>8</sub>- to C<sub>18</sub>-BACs and C<sub>10</sub>-DADMAC on *E coli*.<sup>24</sup> The rate of adaptation of bacteria was faster for BACs, as DADMACs are more effective than BACs at inactivating bacteria and viruses.<sup>24</sup> More gene mutations and higher resistance levels developed, however, with exposure to DADMACs over an extended period.<sup>24</sup> Further studies are needed to understand the human and aquatic health risks posed by the reliance on QACs and associated antibiotic resistance.

It is important to investigate how the increased use of QAC-containing products during the pandemic has impacted their levels in wastewater and their removal during treatment. QACs have been shown to potentially disrupt and impact both the nitrification and denitrification processes in wastewater treatment plants.<sup>25,26</sup> They may also pose a risk to wildlife as they can be toxic at relatively low concentrations.<sup>4</sup> This study was undertaken to

evaluate the concentrations of 21 QACs in municipal wastewater influent, effluent, and biosolids from three treatment plants in the greater San Francisco Bay Area. In addition, San Francisco Bay water, Bay sediment, and urban stormwater runoff samples collected as part of ongoing monitoring by the RMP were analyzed to evaluate the presence of QACs in this aquatic environment.

### Methods & Materials

Seven BACs, five ATMACs, two EtBACs, and seven DADMACs were monitored based on those in greatest use. The alkyl chain length of each compound is denoted by  $C_x$  with  $x$  representing the number of carbons. For example, the compound dioctyldimethylammonium chloride is denoted as  $C_8$ -DADMAC. Ultrapure water (18.2 M $\Omega$ •cm at 25 °C) from a Milli-Q<sup>®</sup> system was used for sample blanks and water used in solid phase extraction.

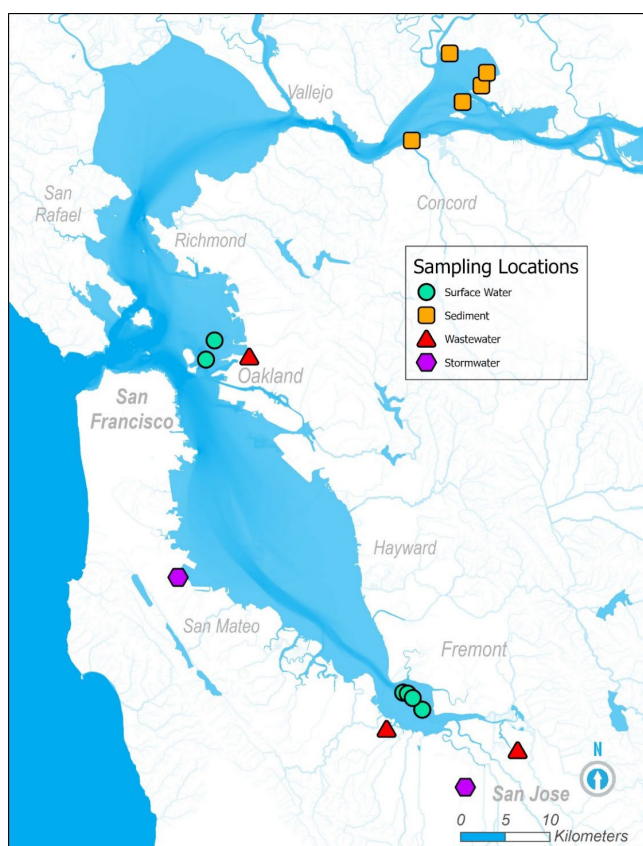
Tetraalkylammonium (TAA) compounds were used as internal surrogate standards (ISTDs).

### *Sample collection*

Composite wastewater effluent, influent and biosolids samples were collected beginning in early 2020 through the end of 2022 from three municipal wastewater treatment plants in the Bay Area (Figure 1). Bottles were soaked in Alconox<sup>®</sup> overnight, rinsed with deionized water then soaked in an acid bath (1 M HCl) overnight. After rinsing with ultrapure water, they were autoclaved for 30 minutes prior to sample collection. Samples were collected by plant personnel as part of their routine water quality analyses. The details of the wastewater treatment plants, including size and treatment methods, are listed in Table 1. The approximate volume of each sample collected was 1 L, and because sample extraction occurred in Minnesota, samples were frozen at -4 °C in the collection bottles and shipped on ice. When

extraction commenced, the samples were defrosted overnight and extracted the following morning. This allowed the samples to reach room temperature and large particulate matter to settle. Biosolids were collected in metal tins that had been cleaned with Alconox® and solvent rinsed and were frozen at -4 °C and shipped on ice as well. Solids were freeze dried or oven dried to remove water before extraction.

Sediment and surface water samples were taken from San Francisco Bay in 2020 and 2021, respectively, and stormwater samples were collected in 2022 (Figure 1). The stormwater and surface water samples were collected and stored the same way as wastewater samples, and sediment samples were collected and stored in the same manner as biosolids.



**Figure 1.** Sampling locations in San Francisco Bay.

*Wastewater QAC extraction method*

A method was adopted that combined the water extraction method of Pati and Arnold<sup>27</sup> and the dust extraction method of Zheng,<sup>27,28</sup> because there was particulate matter in the samples even after settling, which clogged solid phase extraction (SPE) cartridges. For each sample, two sub-samples were processed (one spiked with QACs [see Table 2] to assess recovery and one unspiked). Each sample (250 g for effluent, 50 g for influent) was weighed into a combusted glass flask. A ceramic Buchner funnel with combusted (500 °C, 4 hours) glass fiber filters (47 mm, Pall corporation) were used to filter the samples. After filtering, the filters were placed in a centrifuge tube, amended with 4 mL acetonitrile (ACN), sonicated for an hour at room temperature, and then centrifuged for 5 min at 1107 RCF.<sup>28</sup> After this, the ACN was carefully decanted into a combusted glass centrifuge tube, and the extraction steps were performed twice more for a total filter extraction volume of 12 mL ACN.

SPE of the filtered water was performed with 6 mL Oasis WCX cartridges (150 mg, 30 µm, Waters Corporation). Cartridges were first conditioned with 5 mL methanol (MeOH) and 5 mL ultrapure water. The filtered water was then loaded at a rate of approximately 5 mL/min. After the samples had been fully loaded, cartridges were washed with 5 mL ultrapure water and 5 mL MeOH, and then samples were eluted with 9 mL of ACN with 2% formic acid (FA). The combined filter and SPE extracts were then evaporated to dryness under N<sub>2</sub> gas in a water bath at 40 °C. The extracts were reconstituted in 500 µL of ACN and filtered through a 0.2 µm PTFE filter, before adding 450 µL of ultrapure water to the sample vials, and 50 µL of a 2000 µg/L ISTDs solution was added for a total volume of 1 mL. Samples were frozen at 4 °C until analysis.

Large particles were settled out prior to filtration, but the filters captured some suspended particles, so the final reported concentrations represent “total dissolved QAC,” defined as the sum of dissolved QACs, any QACs associated with dissolved organic matter, and QACs bound to small suspended particles captured by the filter.

The biosolids and sediments were extracted with a 2% FA (v/v) in ACN solution. First, the samples were weighed (50 mg of biosolid or 250 mg of sediment) into a plastic centrifuge tube, then they were spiked with ISTDs and QACs (see Table 1), and then 5 mL of 2% FA in ACN was added. The samples were vortexed for 15 seconds, sonicated for 1 hour at 30 °C, centrifuged for 5 minutes, and decanted into a volumetric flask. This process was repeated once more, and then the samples were diluted with 100 mL of a 250 mM sodium citrate solution. This was done to ensure a circumneutral pH, which is required for the SPE cartridges to perform properly. The samples were then processed via SPE, following the same procedure described for water samples. After the samples were eluted and blown down with N<sub>2</sub>, the sediment extracts were reconstituted the same way as water samples, but biosolids were reconstituted in 2 mL ACN and then two fractions were taken (see footnote in Table 1) and added to an LC-MS vial. ACN, ultrapure water and ISTDs were added so that the final volume of the extract in the vial was still 1 mL.

**Table 1.** Details of wastewater treatment plants. All are in urban areas.

<b>Treatment Plant</b>	<b>Approximate Treatment Capacity</b>	<b>Treatment<sup>1</sup></b>	<b>Key Features</b>
Plant X	> 30 MGD	Tertiary (N)	Gravel/sand/anthracite filters, UV
Plant Y	> 150 MGD	Tertiary (DN)	Gravel/sand/anthracite filters, NaOCl
Plant Z	> 120 MGD	Secondary	Aeration with O <sub>2</sub> , NaOCl

<sup>1</sup>N = nitrification, DN = nitrification/denitrification. Tertiary treatment includes a filtration step.



**Table 2.** Final LC-MS vial concentration of surrogate standards added to both samples and QACs added to spike samples.

	Influent (µg/L)	Effluent (µg/L)	Surface Water/ Stormwater (µg/L)	Sediments (µg/L)	Biosolids <sup>1</sup> (µg/L)	Dilute Biosolids <sup>2</sup> (µg/L)
Surrogate Standards	200	100	50	100	200	40
QACs in spikes	400	200	100	200	200	40

<sup>1</sup>QAC concentrations are so high in biosolids that the sample, usually reconstituted in 500 µL ACN, was reconstituted in 2 mL ACN and a 500 µL aliquot was taken for analysis.

<sup>2</sup>A 100 µL aliquot was extracted for LC-MS analysis, as certain compounds are present in such high amounts that the first dilution step was not enough.

### *Sample and data analysis*

Samples were analyzed by liquid chromatography triple quadrupole mass spectrometry (LC-MS/MS). Most QACs were target compounds for which authentic standards were used, but non-target analytes included C<sub>6</sub>- and C<sub>8</sub>- BAC, C<sub>16</sub>-ATMAC, and C<sub>14</sub>-DADMAC. The calibration curve of QAC that was most similar in structure and instrumental retention time was used to calculate the concentrations of the non-targets (C<sub>10</sub>-BAC was used for C<sub>6-8</sub>-BAC, C<sub>14</sub>-ATMAC for C<sub>16</sub>-ATMAC, and C<sub>12</sub>-DADMAC for C<sub>14</sub>-DADMAC).<sup>27</sup> To correct for QAC losses during extraction, all analyzed concentrations were corrected for the relative recovery of the respective spiked sample.<sup>7</sup> Due to low recoveries, some concentrations of long chain DADMACs, as well as C<sub>18</sub>-ATMAC and C<sub>18</sub>-BAC, were corrected using a 25% recovery to provide a conservative concentration value (i.e., if a sample's relative recovery was <25%, those samples were corrected for 25% recovery). The limits of detection (LOD) ranged from 0.002 ng/L to 8 ng/L with C<sub>10</sub>-DADMAC and C<sub>18</sub>-DADMAC with the highest LOD. For all compounds, the LODs are below available toxicity thresholds. Concentrations of individual QACs are reported, as are the sum by compound class. The overall sum of all BACs, EtBACs, DADMACs, and ATMACs is referred to as [QAC]<sub>Total</sub>.

## Results and Discussion

Influent from all three plants had median [QAC]<sub>Total</sub> ranging from 33 – 58 µg/L and maximum [QAC]<sub>Total</sub> ranging from 100 – 198 µg/L (see Table 4). Influent from Plant X had the highest maximum [QAC]<sub>Total</sub> (198 µg/L) and highest median [QAC]<sub>Total</sub> (33 µg/L) of influents from the three plants. Interestingly, effluent from Plant X had a lower maximum [QAC]<sub>Total</sub> (5.7 µg/L) than Plant Y (10.9 µg/L). Effluent from Plant X also had the lowest median compared to effluent from Plants Y and Z (0.358, 0.419 and 0.981 µg/L, respectively). This may indicate that while QAC levels in influent from Plant X are high, QACs are being removed more successfully from the liquid effluent than in Plants Y and Z. The effluent from all three plants had median [QAC]<sub>Total</sub> ranging from 0.358 – 0.981 µg/L and maximum [QAC]<sub>Total</sub> ranging from 2.2 – 10.9 µg/L.

In influent from all three plants, the QAC with the highest median concentration was C<sub>14</sub>-BAC, and the second highest (third highest for Plant Y) was C<sub>8/10</sub>-DADMAC (Table 4). These are both QACs that are antimicrobials in many disinfectants. C<sub>14</sub>-BAC is the BAC used in the highest concentrations in most disinfectants. Contrastingly, the QACs with the highest medians in effluent were C<sub>18</sub>-DADMAC (Plants Y and Z) and C<sub>14</sub>-ATMAC (Plant X). Neither of these QACs are detected in high concentrations in influent. This potentially indicates some QACs are better removed than others.

Extracting QACs from biosolids provides information on the QACs that are removed by sorption rather than biodegradation during activated sludge treatment. There was a substantial amount of QACs in biosolids, with medians from all three plants greater than 100 mg QAC<sub>total</sub>/kg biosolids, dry weight (dw) (Table 4). These are substantially higher levels compared to concentrations of other organic contaminants that have been detected in

biosolids.<sup>29,30</sup> A review study of emerging organic contaminants in biosolids showed that, with the exception of some steroids, concentrations of QACs in biosolids are much higher than most other organic contaminants.<sup>29,30</sup> Another review showed a similar trend; the amount of QACs detected in this study were higher than almost all other classes of organic compounds, with the exception of linear alkylbenzene sulphonates (LAS).<sup>30</sup> These results also potentially indicate that a large fraction of QACs are being removed through sorption to sludge rather than by degradation. Biosolids from Plant Z had a higher maximum [QAC]<sub>Total</sub> (655 mg/kg dw) and the highest median [QAC]<sub>Total</sub> (238 mg/kg dw) compared to the other two plants.

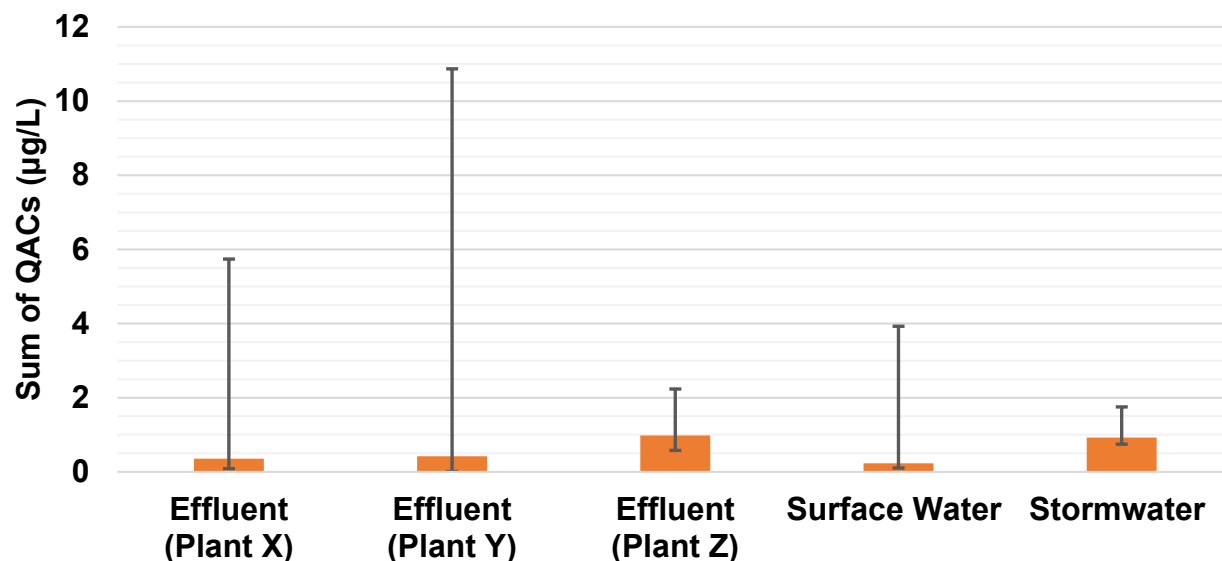
The QAC with the highest median concentration in biosolids from Plants X and Z (and second highest from Plant Y) was C<sub>8/10</sub>-DADMAC (33, 74, and 25 mg/kg dw, respectively). C<sub>14</sub>-BAC had the second highest concentration in biosolids from Plant Z (22 mg/kg dw) and third highest from Plant X (17 mg/kg dw). C<sub>8</sub>-DADMAC, another commonly used QAC in disinfectants, had the second highest median in biosolids from Plant X (17 mg/kg) and first highest in biosolids from Plant Y (56 mg/kg dw). Overall, the biosolids contained high concentrations of QACs, and the QACs detected in the highest concentrations are similar to those detected in the highest concentrations in influents. Adsorption to biosolids provides another potential route to the environment. Additional research would be needed to assess the potential for sorbed QACs to migrate from biosolids to groundwater or surface water.

Overall, the sediment and water samples from the San Francisco Bay had lower QAC levels than treatment plant effluent and biosolids, respectively. In sediments, the maximum [QAC]<sub>Total</sub> was 0.56 mg/kg dw and the median [QAC]<sub>Total</sub> was 0.09 mg/kg dw, indicating that QACs are present in sediments. Unfortunately, there was an instrument issue with C<sub>8</sub>-DADMAC, and the concentration of this compound could not be measured in sediment

samples. Therefore, C<sub>8</sub>-DADMAC is not included in the [QAC]<sub>Total</sub>. The QACs with the highest median concentrations were C<sub>18</sub>-DADMAC (0.04 mg/kg dw), C<sub>12</sub>-BAC (0.02 mg/kg dw), and C<sub>8/10</sub>-DADMAC (0.01 mg/kg dw). These sediment samples were collected from Suisun Bay, a northern subembayment (Figure 1), which had previously shown the highest total levels of QACs in sediment at a single site in a 2018 analysis (1.2 mg/kg dw).<sup>31</sup> The sites sampled in this study were in different parts of Suisun Bay than the 2018 sample, which may suggest a specific source closer to the 2018 site. Although QACs are persistent in aquatic sediment, available ecotoxicity data indicate relatively low sediment toxicity, and concentrations are far below available predicted no effect concentrations (PNECs).<sup>31</sup>

Surface water samples were collected in different areas relative to sediment samples, and were focused on the Central and Lower South Bays (Figure 1). The maximum [QAC]<sub>Total</sub> in surface water samples was 3.93 µg/L and the median [QAC]<sub>Total</sub> was 0.231 µg/L (Table 4). The sample with 3.93 µg/L QACs was primarily due to a much higher concentration of C<sub>8</sub>-DADMAC (3.76 µg/L) in one sample compared to the rest. This could potentially indicate an outlier, contamination during extraction, or a sudden influx of C<sub>8</sub>-DADMAC into the surface water right before it was measured. If that data point is eliminated, the maximum [QAC]<sub>Total</sub> was 1.09 µg/L. The median concentration of QACs in surface water was lower than the median concentration of QACs in effluents, but not substantially so (Figure 2; Table 4). This shows that QACs are present in the surface water environment at high ng/L or low µg/L concentrations. The individual QACs with the highest median concentrations in surface water samples were C<sub>18</sub>-DADMAC (0.040 µg/L), C<sub>16</sub>-ATMAC (0.026 µg/L), C<sub>14</sub>-ATMAC (0.021 µg/L), and C<sub>14</sub>-BAC (0.011 µg/L). There is no clear indication that QACs concentrations are higher in the Lower South Bay, which would have been expected due to the higher influence of wastewater and

limited tidal flushing in this subembayment relative to others.<sup>32</sup> These results suggest contributions from non-point sources may be more significant than previously monitored chemicals in the Bay.



**Figure 2.** Comparison of the sum of QACs detected in effluent, surface water, and stormwater. The bars denote the median levels detected with the error bars indicating the minimum and maximum values detected for each matrix.

A few stormwater runoff samples were collected from urban watersheds (imperviousness 54-62%) in 2021 after a large storm event (4.3 – 5.4 cm). The maximum [QAC]<sub>Total</sub> in these samples was 1.75 µg/L and the median [QAC]<sub>Total</sub> was 0.838 µg/L (Table 4). The individual QACs with the highest median concentrations in stormwater samples were C<sub>18</sub>-DADMAC (0.181 µg/L), C<sub>14</sub>-BAC (0.122 µg/L), and C<sub>16</sub>-BAC (0.69 µg/L). These are different QACs than those detected in the highest concentrations in surface water, indicating that there are likely different sources of QACs in urban stormwater runoff. The stormwater samples also had a generally higher maximum (excluding C<sub>8/10</sub>-DADMAC from surface water) and higher minimum concentrations than surface water (Figure 2; Table 4). These intriguing results

suggest opportunistic stormwater monitoring could provide valuable information for water quality managers.

Available ecotoxicity data indicate that QACs can be toxic to aquatic life at relatively low concentrations. For individual compounds with available ecotoxicity data (C<sub>12</sub>-BAC, C<sub>14</sub>-BAC, C<sub>18</sub>-BAC, C<sub>14</sub>-ATMAC, C<sub>16</sub>-ATMAC, C<sub>18</sub>-ATMAC, C<sub>12</sub>-ETBAC, C<sub>14</sub>-ETBAC, C<sub>8</sub>-DADMAC, C<sub>10</sub>-DADMAC, and C<sub>14</sub>-DADMAC), maximum concentrations of all but C<sub>12</sub>-BAC, C<sub>14</sub>-ATMAC, and C<sub>8</sub>-DADMAC are below European Chemicals Agency (ECHA) freshwater and marine PNECs as highlighted in Table 3. The C<sub>12</sub>-BAC 90<sup>th</sup> percentile concentration of 53 ng/L exceeds the marine PNEC of 42 ng/L,<sup>33</sup> the C<sub>14</sub>-ATMAC 90<sup>th</sup> percentile concentration of 66 ng/L exceeds both the C<sub>14</sub>-ATMAC freshwater PNEC of 26 ng/L and the marine PNEC of 2.6 ng/L,<sup>34</sup> and the C<sub>8</sub>-DADMAC 90<sup>th</sup> percentile concentration of 1882 ng/L exceeds both the C<sub>8</sub>-DADMAC freshwater PNEC of 1000 ng/L and the marine PNEC of 100 ng/L,<sup>35</sup> indicating these compounds may pose a risk to aquatic life in San Francisco Bay.

**Table 3.** Comparison of available marine ecotoxicity thresholds to 90<sup>th</sup> percentile concentrations of QACs in surface water.

QAC	Marine Ecotoxicity Thresholds (ng/L)	90th Percentile Concentration in Surface Water (ng/L)
C <sub>12</sub> -BAC	42	53
C <sub>14</sub> -ATMAC	2.6	66
C <sub>8</sub> -DADMAC	100	1882
Sum of BACs	23*	128
Sum of ATMACs	2.6*	136
Sum of DADMACs	100*	2002
Sum of QACs (BACs, DADMACs, & ATMACs)	100	1036

\*Based on the lowest available individual compounds threshold within the subclass.

Further, QAC mixtures are likely to have additive effects,<sup>4</sup> but robust ecotoxicity thresholds for QAC mixtures in surface waters have not yet been derived. Hora et al. calculated a simplified, general PNEC for QACs of 100 ng/L using available *Daphnia magna*

acute toxicity data for BACs, DADMACs, and ATMACs.<sup>7</sup> The 90<sup>th</sup> percentile [QAC]<sub>Total</sub> of 1036 ng/L in Bay surface water exceeds this PNEC by a factor of ten; however, this threshold has a high degree of associated uncertainty due to its use of a protective assessment factor of 1000. Given the likelihood of additive toxicity, it may be appropriate to compare QAC subclass sums with the lowest available individual compound threshold within that subclass. Using this approach, BACs, ATMACs, and DADMACs may all be a concern for Bay biota (Table 3). The 90<sup>th</sup> percentile of the sum of BACs (128 ng/L) exceeds the C<sub>18</sub>-BAC marine threshold of 23 ng/L,<sup>36</sup> the 90<sup>th</sup> percentile sum of ATMACs further exceeds the C<sub>14</sub>-ATMAC PNECs, and the 90<sup>th</sup> percentile of the sum of DADMACs further exceeds the C<sub>8</sub>-DADMAC PNECs and the C<sub>10</sub>-DADMAC marine threshold of 1100 ng/L.<sup>37</sup>

Although the available data point to ecotoxicity threshold exceedances with risk quotients between 1 – 50 for BACs, ATMACs, and DADMACs, the small sample size (n = 6) indicates a need for further surface water monitoring of QACs before they can be placed in a more definitive risk category such as the Moderate Concern category in the RMP's tiered risk-based framework for emerging contaminants. Uncertainties in the future trends of QAC use due to the quickly evolving COVID response also contribute to our recommendation for QACs to remain in the Possible Concern category. Additional Bay water monitoring is recommended to supplement this limited dataset and provide a more robust basis for risk evaluation.

## Conclusions

Overall, analysis of all samples shows that QACs are present in multiple environmental compartments including surface water, sediments, and urban stormwater runoff. While wastewater treatment plants are removing QACs, as evidenced by much lower concentrations

in effluent than influents, the levels present in treated wastewater effluent, when summed as a compound class, are at higher concentrations than many other contaminants of emerging concern. In addition, high amounts of QACs were found sorbed to biosolids, which could provide yet another environmental release route. Wastewater effluents and stormwater runoff are both pathways for QACs to enter San Francisco Bay, with total QAC concentrations on the order of hundreds of ng/L to low µg/L in both pathways. BACs, ATMACs, and DADMACs may pose risk to Bay aquatic biota, although toxicity risk screening is hampered by a lack of data for some compounds. However, we recommend QACs remain in the Possible Concern category in the RMP's tiered risk-based framework for emerging contaminants until additional Bay water data are available.

The QACs detected in wastewater influent in the highest concentrations are those commonly used in disinfectant products, indicating that disinfectants are likely a large source of QACs to wastewater. In contrast, QACs that are antimicrobials in disinfectants were also found to be in stormwater, C<sub>18</sub>-DADMAC, which is not a disinfectant ingredient, was the QAC present in the highest median concentration in these samples. It is unclear if this result is an analytical issue, or if there are other uses of this QAC that lead to its presence in stormwater runoff. This suggests further method development may be useful to expand the list of analytes monitored to fully capture the breadth of QACs currently in use.

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