

An Assessment of Ambient Water Quality and Challenges with Access to Water and Sanitation Services for Individuals Experiencing Homelessness in Riverine Encampments

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Abstract

Individuals experiencing unsheltered homelessness face significant barriers to accessing water, sanitation, and hygiene services, but the risks associated with this lack of access and barriers to service provision have been largely understudied. We analyzed water samples upstream and downstream of three homeless encampments in the San Diego River watershed and interviewed service providers from public and nonprofit sectors to assess local perceptions about challenges and potential solutions for water and sanitation service provision in this context. Water upstream from encampments contained detectable levels of caffeine and sucralose. *Escherichia coli* concentrations downstream of the encampments were significantly greater than concentrations upstream, but there was no significant change in the concentrations of other pollutants, including caffeine and sucralose. The HF183 marker of *Bacteroides* was only detected in one sample upstream of an encampment and was not detected downstream. Overall, there was insufficient evidence to suggest that the encampments studied here were responsible for contributing pollution to the river. Nevertheless, the presence of caffeine, sucralose, and HF183 indicated that there are anthropogenic sources of contamination in the river during dry weather and potential risks associated with the use of this water by encampment residents. Interviews with service providers revealed perceptions that the provision of water and sanitation services for this population would be prohibitively expensive. Interviewees also reported perceptions that most riverbank residents avoided contact with service providers, which may present challenges for the provision of water and sanitation service unless trust is first built between service providers and residents of riverine encampments.

Keywords: caffeine; dry weather; fecal pollution; social science and engineering collaboration; sucralose; water quality

Introduction

FOR DECADES, THE United States has experienced a homelessness crisis (Edelman and Mihaly, 1989; Dreyer, 2018), which affects the mental and physical health of many people, including children (Schifalacqua *et al.*, 2019), wo-

men (Oudshoorn *et al.*, 2018), and sexual minorities (Corliss *et al.*, 2011). Obstructive lung disease, diabetes, cancer, asthma, and heart disease are several of the chronic health conditions that have been associated with homelessness (Ramin and Svoboda, 2009).

Lack of access to health care and otherwise poor living conditions also place un-housed people at higher risk for a range of acute communicable diseases, including bacterial infections (Badiaga *et al.*, 2008) and skin infections (Gelberg *et al.*, 1990; Badiaga *et al.*, 2005). Abdominal pain, gastroenteritis, nausea, vomiting, viral infections, and respiratory tract

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infections are some of the most frequent reasons for emergency department use by homeless individuals (Moore *et al.*, 2007).

Acute infectious gastrointestinal and respiratory diseases are largely preventable through the provision of potable water, sanitation, and hygiene services, including hand-washing and excreta disposal (Bartram and Cairncross, 2010; Cairncross *et al.*, 2010; Brown *et al.*, 2013). Personal hygiene has also been found to be a positive protective factor in the mental health of individuals experiencing homelessness (Rosengard *et al.*, 2001).

Although it is largely understudied, individuals experiencing homelessness in the United States have some of the worst access to water, sanitation, and hygiene services (Ares *et al.*, 2017; Environmental Justice Coalition for Water [EJCW], 2018; Moffa *et al.*, 2019). A recent study reported that nearly 1 million people in the United States (a large portion that consists of people experiencing housing insecurity) lack sustained access to at least basic sanitation, which is far higher than the data reported in the World Health Organization and UNICEF Joint Monitoring Program (Capone *et al.*, 2020). Sleeping outdoors, in particular, is a predictor of poor sanitation and hygiene practices among homeless individuals (Leibler *et al.*, 2017).

Open defecation is commonly practiced by unsheltered homeless individuals in urban environments (Frye *et al.*, 2019), especially those who reside near rivers (Flanigan and Welsh, 2020). One study reported that 23% of fresh stools from open defecation sites in Atlanta, GA tested positive for human pathogens, including enterotoxigenic *Escherichia coli*, *Giardia*, norovirus, and *Salmonella* (Capone *et al.*, 2018).

Slightly more than half of all individuals experiencing homelessness in the United States utilize emergency shelters and transitional housing programs, but 211,293 are unsheltered, with nearly one-third of them experiencing chronic unsheltered homelessness (US Department of Housing and Urban Development [US HUD], 2019). Unsheltered individuals often stay in tents or sleeping bags on urban sidewalks or other public urban spaces, where they may be prevented from utilizing public facilities by local authorities (Felner *et al.*, 2020).

However, homelessness also exists in natural spaces outside of the public view, especially near urban waterways, which provide cooler, shaded areas with water for washing, cooking, drinking, and fishing (DeVuono-Powell, 2013; Palta *et al.*, 2016; Demyers *et al.*, 2017). Based on data reported by Flanigan and Welsh (2020), which drew from interviews with 84 individuals experiencing homelessness in San Diego, CA, individuals at riverbank encampments were 1.9 (95% confidence interval [CI]: 1.1–3.0) times as likely to practice open defecation, and 2.8 (95% CI: 0.7–11.6) times as likely to use untreated river water for nonpotable purposes, compared with non-river dwelling individuals.

Despite the fact that the latter results from Flanigan and Welsh (2020) were not statistically significant at the 0.05 level, the fact that 41 out of 56 (73%) interviewed river-dwelling individuals reported the practice of open defecation at their encampments and 11 out of 56 (20%) interviewed river-dwelling individuals reported the use of river water for nonpotable purposes highlights the potential public health risks faced by this population based on their lack access to water and sanitation services.

The quality of water available for nonpotable use at riverside homeless encampments and the relative contribution of nonpoint sources of fecal pollution to rivers, particularly

from homeless encampments, are poorly understood (Ahmed *et al.*, 2019). Human fecal contamination to urban rivers, which, in the case of two southern California rivers, was found to originate mainly from sewage exfiltration (Sercu *et al.*, 2009; Pinongcos, 2020), results in detectable levels of human pathogens during storms (Steele *et al.*, 2017). If this contamination also occurred during dry weather, when people at riverbank encampments are more likely to use the water, it could pose a risk for homeless individuals.

One study reported that the annual probability of infection for homeless individuals using river water for bathing or washing personal belongings exceeds 88% and even approaches 100% for some pathogens (Donovan *et al.*, 2008). Further, the lack of toilet access at riverbank homeless encampments has been postulated to be a possible source of human fecal contamination to urban waterbodies. For example, Steele *et al.* (2017) reported the presence of HF183 during rain events at 13 different sampling locations throughout the San Diego River watershed, with concentrations of 10–10,000 gene copies (gc) per 100 mL. Based on these results, the authors suggested that human fecal contamination was not from a single source but rather was diffuse and possibly included homeless encampments.

The goal of the present study was to characterize water quality and sanitation challenges at riverbank homeless encampments during dry weather conditions. Using a mixed-methods approach, we assessed microbiological and physical–chemical quality of river water at locations directly upstream and downstream of three riverbank homeless encampments in San Diego, CA to understand the potential risks associated with using river water for nonpotable purposes, and to understand whether the encampments were causing any significant changes in water quality downstream. We also conducted interviews with public sector and nonprofit service providers and key informants who do outreach with individuals experiencing homelessness, to understand their perceptions and opinions about water and sanitation challenges at riverbank encampments.

Methods

Sample collection and water quality analysis

We collected water samples from the river directly upstream and downstream of three different homeless encampments and analyzed them for the following water quality parameters: phosphate, nitrate, total dissolved nitrogen (TDN), dissolved organic carbon (DOC), dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity, pH, *E. coli*, enterococci, coliphage PhiX174, and HF183 (gene target from *Bacteroides dorei*).

Reconnaissance visits were conducted at nearly a dozen sites with riverbank homeless encampments to determine the feasibility of sample collection. Candidate field sites for sample collection were evaluated based on evidence of an active homeless encampment within close proximity (~200 m) of the riverbank, the presence of dry season flow, and whether or not the site permitted access for sample collection without disturbing privacy or trespassing. We also tried to focus on sites with lower flow rates, where anthropogenic sources of pollution between upstream and downstream sampling sites would be easier to detect.

Three sites were identified that generally met these criteria (Fig. 1). One of the sites was located on the main stem of the San Diego River south of the Fashion Valley shopping center,

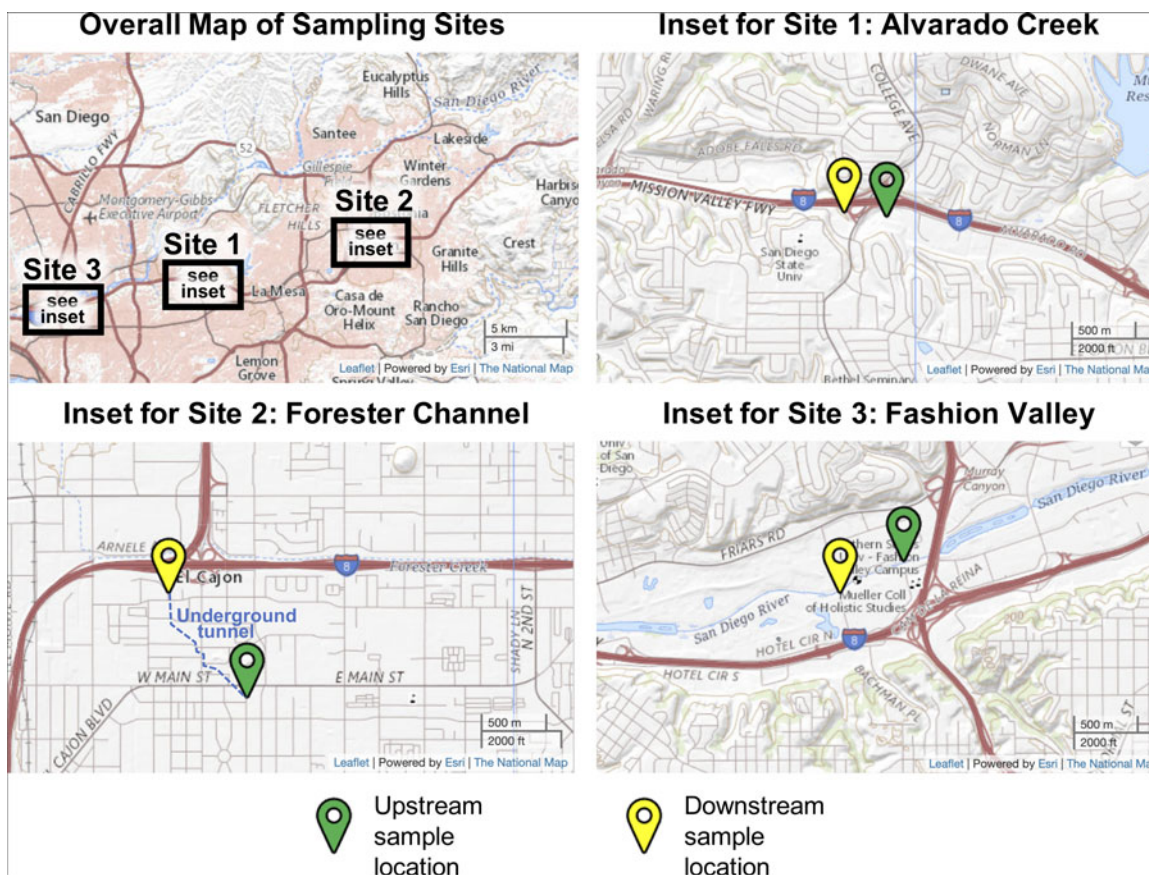


FIG. 1. Upstream and downstream sampling locations in the San Diego River and its tributaries.

~ 5 km upstream from the ocean outfall. The other two sites were located further upstream, on tributaries to the San Diego River: a section of Alvarado Creek adjacent to San Diego State University; and an unnamed channelized tributary of Forester Creek (referred to here as Forester Channel).

Paired upstream and downstream grab samples were collected between June and November 2018 (Alvarado Creek), between June and August 2019 (Forester Channel), and in October and November 2018 (Fashion Valley), on 4–8 different dates per site during dry weather conditions ($N=20$ total paired samples across all three sites).

The sample size was determined by using a power calculation ($\alpha=0.05$, $\beta=0.20$) based on the desire to detect a 0.5- \log_{10} difference in the concentrations of microbial indicators between upstream and downstream samples. The presence of individuals within the encampments subsequently decreased at the Alvarado Creek and Fashion Valley sites after sampling initiated but persisted at the Forester Creek site for the duration of sampling.

An Accumet AP85 multiparameter water quality meter was used to measure pH, water temperature, electrical conductivity, and TDS. A YSI Pro meter was used to measure DO. Within 6 h of collection, samples were also analyzed for *E. coli* and enterococci by using the Colilert and Enterolert methods, respectively, with the IDEXX Quanti-Tray 2000 system. The most probable number (MPN) and 95% CIs were calculated by using maximum likelihood estimation. Bacteria and viruses were also concentrated from 400 mL samples by using membrane filtration with adsorption–extraction (Symonds *et al.*, 2014; Ahmed *et al.*, 2015; Verbyla *et al.*, 2016).

Briefly, sample pH was adjusted to 3.0–3.5 with 1.0 M acetic acid, then vacuum-filtered through 0.45- μm mixed cellulose ester membranes (HAWP type; Millipore), which were immediately placed into bead-beating tubes (lysis matrix E; MP Biomedical) for nucleic acid extraction by using the PowerViral RNA/DNA Kit (Qiagen), following the manufacturer's recommendations. Nucleic acids were stored at -80°C and analyzed for HF183 and PhiX174 by using the QX200 droplet digital polymerase chain reaction (ddPCR) system (Biorad), with previously published assays (Table 1) using 900 nM of each primer and 250 nM of probe. Thermocycling conditions were 95°C for 10 min followed by 40 cycles of 94°C for 30 s, then 60°C for 1 min, and a final step of 98°C for 10 min. Quality control (QC) guidelines used were based on Huggett *et al.* (2013).

Custom gBlocks containing the target amplicons with at least 10 bp on either side of the primers (IDT) were quantified by Qubit (using the $1\times$ double-stranded DNA [dsDNA] HS Assay), then serially diluted, and finally analyzed at concentrations between 1 and 1,000 copies per reaction to determine limits of detection (LODs) as previously described (Verbyla *et al.*, 2016). The LOD were 47 copies per reaction for HF183 and 2 copies per reaction for PhiX174. Considering the sample volumes filtered, this was generally equivalent to 118 copies per 100 mL for HF183 and 5 copies per 100 mL for PhiX174.

Samples were filtered with precombusted (500°C for 2 h) and prefiltered (ultrapure water) 0.7 μm glass fiber filters. Nitrate and phosphate were quantified by using Hach kits, following the manufacturer's standard operating procedures (Hach Methods 8039 and 8048). In brief, 10 mL of the filtered

TABLE 1. PRIMERS AND PROBES USED FOR THE DETECTION OF HF183 AND PHIX174

Assay	Primers/probe sequences (5' → 3')	Amplicon length (bp)	References
HF183/BacR287	F primer ATCATGAGTTCACATGTCCG R primer CTTCTCTCAGAACCCCTATCC Probe ^a /6-FAM/ CTA+ATGGAAC+G+CA+T+CCC/IABkFQ/	191	Green <i>et al.</i> (2014)
PhiX174	F primer (ΦX174): CGCCATTAATAATGTTTTCCGTAA R primer (ΦX174): CATCCCGTCAACATTCAAACG Probe (ΦX174):/6-FAM/ CGCCTTCCATGATGAGA/MGB/	73	Myers <i>et al.</i> (2009)

+, Indicates locations of extra methylene bridges.

^aLNA probe (Integrated DNA Technologies).

6-FAM, 6-carboxyfluorescein (on 5' end); IABkFQ, Iowa Black[®] FQ quencher (on 3' end); LNA, locked nucleic acid; MGB, minor groove binder.

samples was added with powder pillows in a sample cell, and the absorbance was measured by using the Hach DR900 system, set to the programs 355 N Nitrate HR PP (Nitrate) and 490 P React PV (Phosphate Reactive).

DOC and TDN were measured by using a high-temperature combustion method with a Shimadzu TOC-L Total Organic Carbon Analyzer. Blanks of ultrapure water were run every 10 samples and 15% of the samples were run in duplicate. Samples (400 mL) were extracted and analyzed for caffeine and sucralose concentrations following U.S. EPA Method 1694, using an Agilent 6460 Triple Quad liquid chromatography with tandem mass spectrometry system equipped with Agilent Jet Stream Technology. The triple quadrupole mass spectrometry system was operated in the multiple reaction monitoring mode, using the precursor and product ion transitions of the target compounds and their isotopically labeled surrogates to detect the analytes of interest. Liquid chromatography mass spectrometry water was used as field blanks and lab blanks.

Caffeine concentrations were lower than 0.071 µg/L in three field blanks and undetectable in two. Sucralose concentrations were undetectable in four out of five field blanks and 0.001 µg/L in the fifth. One-tailed, paired sample *t*-tests were performed by using Excel for every parameter except for pH and DO, where a two-tailed, paired sample *t*-test was used. Log₁₀-transformed concentrations of microbial pollutants were used for statistical tests, and no data transformations were performed for other parameters.

Perceptions about water and sanitation for residents of riverbank encampments

Data collected by using the Point-in-Time count methodology (Department of Housing and Urban Development [US HUD], 2019) were graciously provided by the Regional Task Force on the Homeless at the census tract level for the San Diego River watershed. Given that this methodology notably underestimates river- and canyon-dwelling individuals, we also collected data from geospatial surveys from trash assessments published online by the San Diego River Park Foundation (2019). Although counting homeless individuals is not the main purpose of these surveys, enumerators typically estimate the number of tents and structures found at encampments, as well as the extent and location of open defecation sites near the river.

To understand local perceptions about challenges and possible solutions for water and sanitation at riverbank homeless encampments, we conducted semi-structured interviews with key informants from two main groups of stakeholders: public sector and nonprofit sector service providers. Public sector

staff included individuals from local government agencies who were involved in the provision of public restrooms for city or county residents. Nonprofit service providers included employees and volunteers of nonprofit organizations that were involved directly or indirectly with interactions or outreach to individuals experiencing homelessness.

Service provider interviews were conducted to contextualize semi-structured interview data from eighty-four individuals experiencing homelessness, and fifty-three of whom resided near the San Diego River (Flanigan and Welsh, 2020). The research protocol was approved by the San Diego State University Institutional Review Board (IRB) under protocol number HS-2018-0190.

Informational interviews were conducted with seven staff members of local nonprofit organizations focused on homelessness services and environmental conservation. Interviewees were selected by first reviewing all known homelessness services organizations with relevant scope of services and geographic reach. After discarding organizations that clearly did not regularly provide services to individuals living in encampments along riverbanks (such as shelters providing only in-house services), we generated a list of 20 organizations that appeared to have some interaction with individuals living along the margins of the river. After reaching out to contacts at each of these organizations, only seven indicated that they could offer some limited information on individuals experiencing homelessness living along the margins of the river, although very few of these staff members' organizations regularly provided services to this population.

Our interview recruitment process revealed that at the time of this research, no organizations actively and regularly engaged in outreach to individuals living along the riverbank, resulting in a population with low levels of service interaction. However, since the time of this research, and based in part on our prior research findings (Flanigan and Welsh, 2020), a local homelessness services organization has partnered with a local environmental organization to provide regular outreach to individuals experiencing homelessness in the river margins.

Field notes were then transformed, coded, and analyzed both quantitatively and thematically by both lead researchers as well as one student researcher who had conducted a handful of the interviews. For open-ended questions, we initially engaged in a process of inductive, thematic coding (Braun and Clarke, 2006) to identify key themes around issues such as survival strategies and perceptions of police. All three researchers engaged in the coding process, and we monitored inter-coder reliability by meeting often during the analysis phase to discuss how we were applying codes and addressing any inconsistencies.

Results and Discussion

Location of riverbank encampments and open defecation sites

According to the Point-in-Time count data, a total of 2,475 individuals, 622 vehicles, and 716 hand-built structures were recorded within the San Diego River watershed; of them, 129 individuals, 20 vehicles, and 104 hand-built structures were located in census tracts adjacent to river lines for the lower San Diego River (downstream of San Vicente Creek) and two of its tributaries (Alvarado Creek and Forester Creek). Data from geospatial surveys along the lower stretch of the San Diego River (San Diego River Park Foundation, 2019) revealed 31 riverbank encampments, with 39 tents in 2017 and 26 encampment sites with 16 tents in 2018. Evidence of open defecation (e.g., visible feces and the presence of anal cleansing materials) was recorded at 16 sites in the 2017 survey and at 13 sites in the 2018 survey. These open defecation sites were located in close proximity to the San Diego River, with 50% found within 60 m of the river margin (Fig. 2).

Water quality and insights about risks of water use

Average flow rates measured during the sampling periods were 12.5 L/s for Alvarado Creek, 5.3 L/s for Forester Channel, and 23.0 L/s for the San Diego River at Fashion Valley. There was no precipitation recorded during sampling or for at least a month before sampling, and flow rates did not vary greatly throughout the duration of the sampling campaigns. Samples collected upstream of the Alvarado Creek, Forester Channel, and Fashion Valley encampment sites, respectively, had mean DOC concentrations of 7.0, 8.5, and 14.0 mg/L; mean TDN concentrations of 0.7, 4.6, and 0.9 mg/L; mean nitrate-N concentrations of 0.3, 3.5, and 0.2 mg/L; and mean phosphate concentrations of 0.5, 0.3, and 0.5 mg/L. The pH was slightly above neutral for all sites (overall average of 8.4), and average electrical conductivity levels were 2,047 $\mu\text{S}/\text{cm}$ for Alvarado Creek and 2,658 $\mu\text{S}/\text{cm}$ for Forester Channel. Caffeine and sucralose were detected in all three sites at overall average concentrations of 0.17 and 0.52 $\mu\text{g}/\text{L}$, respectively.

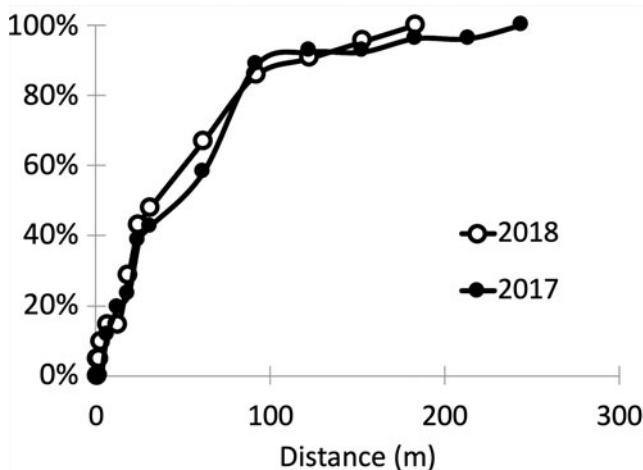


FIG. 2. Cumulative distribution of reported open defecation sites as a function of distance from the river in 2017 and 2018. Fifty percent of sites were located within 60 m from the river margin in both years. Source of data: San Diego River Park Foundation (2019).

Geometric mean concentrations of *E. coli* and enterococci for the upstream samples ($N=8$) from the Alvarado Creek site were, respectively, 52 and 152 MPN per 100 mL. Forester Channel upstream samples showed geometric mean concentrations of 767 MPN per 100 mL for *E. coli* and 2,008 MPN per 100 mL for enterococci ($N=8$). The Fashion Valley upstream site had geometric mean concentrations of 79 MPN per 100 mL for *E. coli* and 155 MPN per 100 mL for enterococci ($N=4$). These concentrations are consistent with a previous report by the San Diego Region Water Board (2017), which showed a geometric mean *E. coli* concentration of 454 MPN per 100 mL in Forester Creek (5 km downstream from the Forester Channel site) and 30 MPN per 100 mL in the San Diego River (6 km upstream from the Fashion Valley site). The bacterial water quality objective for the San Diego River was recently reduced to a 6-week geometric mean of 30 MPN per 100 mL for enterococci and 100 MPN per 100 mL for *E. coli* (CA Water Board, 2019).

Both Forester Creek and the lower section of the San Diego River are designated as water quality limited segments for fecal indicator bacteria in the Clean Water Act Section 303(d) list, and dischargers to the San Diego River were recently issued an investigative order to determine the source of human-associated fecal contamination (Schiff *et al.*, 2016; Arnold *et al.*, 2017). The Water Quality Control Plan for the San Diego Basin (San Diego Region Water Board, 1994) identifies contact water recreation (REC-1) as one of the beneficial use categories for Forester Creek and the lower San Diego River. The REC-1 use category includes recreational activities involving body contact with water, such as swimming, wading, water-skiing, or diving. The use of these rivers for water supply is not permitted, however, as Flanigan and Welsh (2020) demonstrated, on average, one out of every five individuals experiencing homelessness near rivers and canyons reported using the water for nonpotable purposes.

There are no explicit recommendations for *E. coli* and enterococci concentrations in water used in this context. However, NSF/ANSI Standard 350 for onsite water reuse recommends maximum *E. coli* concentrations of 14 MPN per 100 mL on average and 240 MPN per 100 mL for an individual sample (US EPA *et al.* 2012). In Texas, geometric mean concentrations of *E. coli* and enterococci in reclaimed water for nonpotable use must be below 20 MPN per 100 mL. *E. coli* concentrations observed upstream of homeless encampments at all three sites exceeded these recommended limits, indicating a potential risk associated with nonpotable use. However, a recent study suggested that washing hands with water containing <1,000 MPN per 100 mL *E. coli* could still result in an overall reduction of *E. coli* on a person's hands in some settings (Verbyla *et al.*, 2019).

The concentrations of human-associated indicator HF183 were below the method LOD for all samples collected from Alvarado Creek and Forester Channel, although 1 or 2 positive droplets were detected in 4 out of 16 samples from Alvarado Creek. One of the upstream samples from Fashion Valley was positive for HF183, with a concentration of 553 gc per 100 mL. The corresponding downstream sample from that date was a nondetect. HF183 was not detected in any samples from Forester Channel.

Human-associated fecal pollution has been reported in other rivers in Mediterranean climates that experience very little precipitation during the dry season. For example, Sercu *et al.*

(2009) reported the presence of HF183 on 3 consecutive days during the dry season in three separate storm drains and creeks in Santa Barbara, CA, at concentrations as high as 1.5×10^6 gc per 100 mL. Sercu *et al.* (2009) determined that the source of HF183 in their study was exfiltration from old, failing sewer infrastructure. Russell *et al.* (2013) reported the presence of HF183 at concentrations as high as 1.9×10^4 gc per 100 mL in the San Lorenzo River in Santa Cruz, CA, during the dry season. It has been suggested that HF183 concentrations greater than 3.22×10^3 gc per 100 mL could cause a microbial risk that exceeds 36 gastrointestinal illnesses per 1,000 swimming events (Ahmed *et al.*, 2018). Although the concentrations detected in our study were considerably lower than this threshold, the presence of HF183 (as well as caffeine and sucralose) suggests that human fecal pollution may pose risks to individuals experiencing homelessness in riverbank encampments who use the river water for nonpotable purposes.

Insights about fecal pollution from upstream/downstream sampling

The measured changes in the concentrations of fecal indicators and other water quality parameters between upstream and downstream sites and the results of the *t*-tests are shown in Figs. 3 and 4 and in Tables 2 and 3. For *E. coli*, concentrations were mostly greater downstream than they were upstream. The same was not true for enterococci. The magnitude of the increase in the concentrations of fecal indicator bacteria was greater at Forester Channel and Fashion Valley than it was at Alvarado Creek. However, the measured differences at Alvarado Creek were more consistent, as indicated by lower standard deviations (SDs). With a few exceptions, the concentrations of general water quality parameters did not change significantly between upstream and downstream samples. There was large variability from sample to sample for nitrate and DO.

The differences between \log_{10} -transformed *E. coli* concentrations was significant at all three sites, but for enterococci, the difference was only significant at Fashion Valley ($p=0.011$). Maraccini *et al.* (2016) reported no significant difference between the die-off of *E. coli* and enterococci in a freshwater marsh, and Korajkic *et al.* (2013) likewise reported similar decay of *E. coli* and enterococci after 7 days of exposure in freshwater microcosms. In freshwater at temperatures between 13°C and 18.5°C, the persistence of HF183 has been reported to be less than the persistence of enterococci, and the persistence of enterococci was found to be less than that of *E. coli* (Walters and Field, 2009; Jeanneau *et al.*, 2012).

Both *E. coli* and enterococci originate in the feces of warm-blooded animals, but naturalized strains of *E. coli* have been reported to persist and grow in soils and sediments, where they may later leach into surface waters (Byappanahalli *et al.*, 2003; Ishii *et al.*, 2006; Brennan *et al.*, 2010). Therefore, the increase in the concentration of *E. coli* by itself is not necessarily indicative of a human pollution input from the homeless encampments. The Alvarado Creek and Fashion Valley sites were located in nonchannelized sections of the river, with sanitary sewer lines running alongside the river, even crossing over the river at several points. The downstream sampling location for the Fashion Valley site also had more stagnant flow than the upstream site, and ducks were observed nearby the downstream sampling site on several occasions.

For the Forester Channel site, the upstream and downstream locations were on opposite ends of a 1,000-m underground stormwater tunnel, which is entirely lined with concrete and drains an area of approximately three city blocks. The *E. coli* concentrations at that site might indicate a fecal input, but not necessarily from human feces. PhiX174 coliphage is a virus that infects *E. coli*, but despite the significant differences noted in the concentrations of *E. coli* between upstream and downstream samples, the same trend was not observed for PhiX174. The overall geometric mean

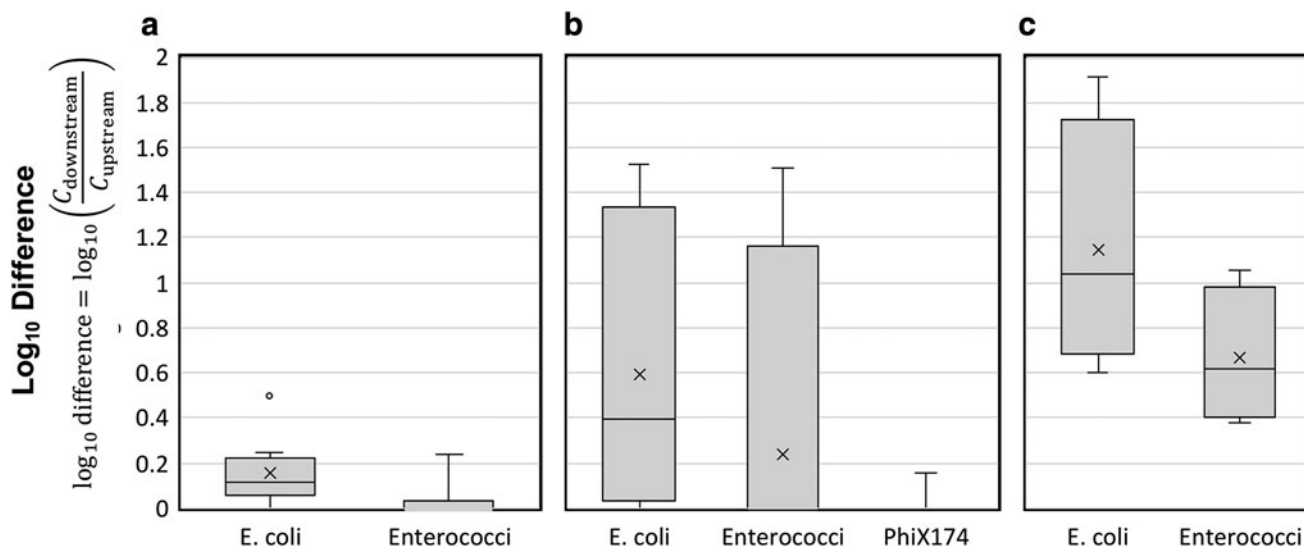


FIG. 3. \log_{10} differences between concentrations of fecal indicator bacteria (*Escherichia coli* and fecal enterococci) and viral fecal indicator PhiX174 for samples collected directly upstream and directly downstream of homeless encampments along the banks of: (a) Alvarado Creek near SDSU ($N=8$); (b) Forester Channel ($N=8$); and (c) the San Diego River at Fashion Valley ($N=4$). Boxes show the interquartile range and the median, and whiskers show the minimum and maximum data points that are within 1.5 times the interquartile range. Plots also show mean values (\times) and any outlier data points (\circ) that are less than or greater than 1.5 times the interquartile range.

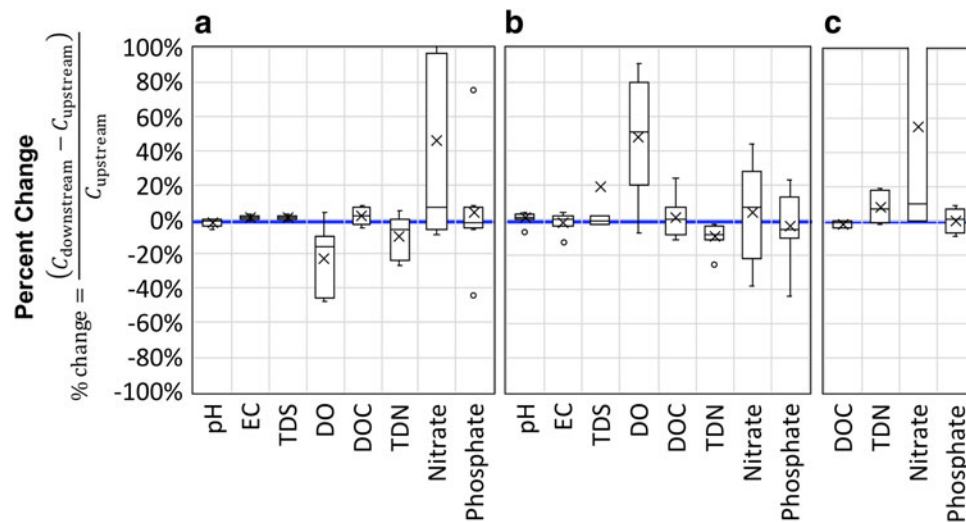


FIG. 4. Percent differences between general water quality parameters for samples collected during dry weather conditions directly upstream and directly downstream of homeless encampments along the banks of: **(a)** Alvarado Creek near SDSU ($N=8$); **(b)** Forester Channel ($N=8$); and **(c)** the San Diego River at Fashion Valley ($N=4$). Boxes show the interquartile range and the median, and whiskers show the minimum and maximum data points that are within 1.5 times the interquartile range. Plots also show mean values (×) and any outlier data points (○) that are less than or greater than 1.5 times the interquartile range.

concentration of PhiX174 at the Forester Channel site was 88 gc per 100 mL. There was no significant difference between upstream and downstream samples; however, the downstream concentrations were lower on average than the upstream concentrations.

HF183 was only detected at Fashion Valley in one upstream sample. Due to the large number of nondetects, it was not possible to perform a t -test for HF183. Thus, there is no evidence that the encampments increase the concentration of human-associated fecal pollution. Despite significant increases in *E. coli*, other water quality data did not provide additional evidence supportive of pollution from the encampments. For example, at Alvarado Creek and Forester Channel, TDN concentrations were significantly lower downstream than they were upstream. The DOC concentrations increased slightly, but the increase was not significant.

Nutrient levels also changed, but these changes were not significant. The DO concentrations significantly changed as well, but in opposite directions—at Alvarado Creek, upstream samples had higher DO levels than downstream samples; but DO levels at Forester Channel were higher downstream than they were upstream.

Figure 5 contains a time series plot of caffeine and sucralose concentrations. At Alvarado Creek, caffeine concentrations increased by 10% on average, but the difference was not significant. Sucralose concentrations also remained nearly the same, with no significant difference between upstream and downstream samples. At Forester Channel, concentrations of caffeine and sucralose increased by an average of 41%, but the differences were not significant. Further, caffeine concentrations were 10% higher upstream (median), but sucralose concentrations were 27% downstream

TABLE 2. MEAN AND MEDIAN DIFFERENCES, STANDARD DEVIATIONS, AND RESULTS OF ONE-TAILED, PAIRED SAMPLE t -TESTS COMPARING THE LOG_{10} -TRANSFORMED CONCENTRATIONS OF *ESCHERICHIA COLI* AND ENTEROCOCCI IN SAMPLES COLLECTED DIRECTLY UPSTREAM AND DIRECTLY DOWNSTREAM OF HOMELESS ENCAMPMENTS

Site	Indicator group	Log_{10} difference in the upstream and downstream concentrations, $\text{log}_{10}(C_{\text{downstream}}/C_{\text{upstream}})$			Sample size (N)	p^a
		Mean	Median	SD^b		
Alvarado Creek	<i>E. coli</i>	0.15	0.12	0.16	8	0.016
	Enterococci	-0.04	-0.05	0.16	8	0.225
Forester channel	<i>E. coli</i>	0.59	0.39	0.65	8	0.018
	Enterococci	0.24	-0.01	0.83	8	0.221
Fashion Valley	<i>E. coli</i>	1.15	1.04	0.56	4	0.013
	Enterococci	0.67	0.62	0.31	4	0.011
Overall pooled (all three sites)	<i>E. coli</i>	0.53	0.30	0.60	20	0.006
	Enterococci	0.21	0.02	0.59	20	0.147

^aOne-tailed, paired sample t -test of log_{10} -transformed concentrations from upstream and downstream samples. The null hypothesis is that upstream and downstream concentrations are equal; the alternative hypothesis is that downstream concentrations are greater.

^b SD of the log_{10} difference between the concentrations in samples collected directly downstream and directly upstream. SD , standard deviation.

TABLE 3. MAGNITUDE OF MEAN AND MEDIAN DIFFERENCES AND STANDARD DEVIATIONS AND RESULTS OF THE PAIRED SAMPLE *t*-TESTS COMPARING THE CONCENTRATIONS OF PHYSICAL-CHEMICAL POLLUTANTS IN SAMPLES COLLECTED DIRECTLY UPSTREAM AND DIRECTLY DOWNSTREAM OF ENCAMPMENTS DURING DRY WEATHER CONDITIONS

Site	Pollutant/parameter	Percent change in the concentrations ^a			Sample size (N)	p ^b
		Mean (%)	Median (%)	SD ^c (%)		
Alvarado Creek	pH	-1.5	-0.3	2.5	8	0.133
	Electrical conductivity	+1.2	+1.1	1.0	8	0.007
	Total dissolved solids	+1.3	+1.5	1.1	8	0.004
	Dissolved oxygen	-23	-16	20	8	0.017
	Dissolved organic carbon	+1.8	+1.8	5.1	8	0.177
	Total dissolved nitrogen	-9.6	-5.4	12	8	0.038
	Nitrate	+46	+7.4	75	8	0.052
	Phosphate	+4.6	-3.9	36	8	0.464
	Caffeine	+11	+1.4	28	4	0.203
	Sucralose	+0.1	+3.4	13	4	0.299
Forester Channel	pH	+1.1	+1.8	3.6	8	0.477
	Electrical conductivity	-1.4	0	5.6	8	0.266
	Total dissolved solids	+20 ^d	-0.3	62 ^e	8	0.225
	Dissolved oxygen	+48	+51	34	8	0.002
	Dissolved organic carbon	+1.5	+0.7	12	8	0.441
	Total dissolved nitrogen	-9.7	-8.6	7.6	8	0.002
	Nitrate	+4.7	+7.3	29	8	0.396
	Phosphate	-3.3	-5.7	21	8	0.265
	Caffeine	+41	-10	139	8	0.251
	Sucralose	+41	+27	106	7	0.350

^aPositive (+) values indicate that downstream concentrations were higher than upstream concentrations, and negative (-) values indicate that upstream concentrations were higher than downstream concentrations. A value of 0% indicates that upstream and downstream concentrations were equal.

^bThe *p*-value from a one-tailed, paired sample *t*-test of the concentrations in samples collected directly upstream and downstream of encampments. The null hypothesis is that upstream and downstream concentrations are equal; the alternative hypothesis is that downstream concentrations are greater (except for pH and dissolved oxygen, where the alternative hypothesis is that the concentrations are not equal, i.e., two-sided test).

^cSD of the percent (%) difference between the concentrations in samples collected directly downstream and directly upstream of homeless encampments.

^dThe high mean value is due to a single set of samples where the upstream concentration was very low and the downstream concentration was comparable to values measured on other dates. This data point is likely an outlier.

^eIf the outlier set of data points is omitted (see footnote d), this SD would be equal to 5.4%.

(median). Water temperatures ranged from 23.1°C (upstream sample on July 3, 2019) to 38.1°C (downstream sample on July 31, 2019), and the water at the downstream sample location was 2.8°C warmer than the water at the upstream sample location on average (SD = 3.0).

Concentrations also changed drastically with respect to sampling date, indicating that sources may be sporadic and

inconsistent. For instance, on August 5, 2019, there was an increase of >350% in downstream concentrations of caffeine compared with upstream levels. The next day, downstream caffeine concentrations were still almost twice as high as upstream concentrations. There were also large spikes in the concentrations of *E. coli* and enterococci on these two dates (Fig. 5). Interestingly, the water temperatures on these dates

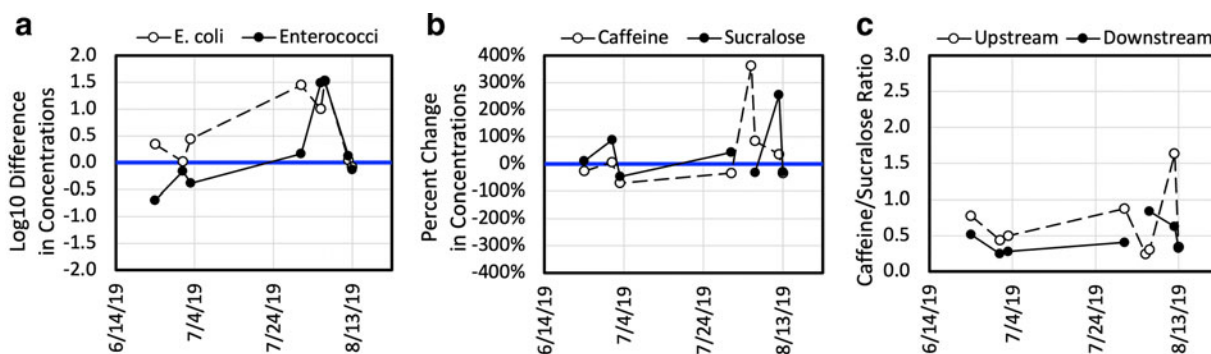


FIG. 5. Time series plots showing: (a) the log₁₀ differences in the concentrations of *E. coli* and fecal enterococci; (b) the percent changes in the concentrations of caffeine and sucralose; and (c) the change in the caffeine/sucralose ratios, at the Forester Channel site. For (a, b), negative values indicate concentrations were higher upstream than they were downstream and positive values indicate concentrations were higher downstream than they were upstream.

were at the higher end (31.7°–34.2°C), and the differences in the water temperatures between the downstream and upstream sample sites on these dates were the lowest. In summary, pollution inputs to these creeks during the dry period may be sporadic, occurring at specific time periods and for short time intervals.

Downstream of the encampment, caffeine/sucralose ratios were consistently below 1.0. Both caffeine and sucralose are excreted by humans in feces and urine, but given that caffeine is more biodegradable and sucralose is more persistent in the environment, higher C/S ratios may indicate more recent inputs of contamination by sewage or human excreta (Cantwell *et al.*, 2018; Pinongcos, 2020). However, the observed increases in caffeine and sucralose were not statistically significant. This, combined with the fact that HF183 was also not detected in the samples, indicates a lack of evidence that these encampments were causing an increase in pollution to the river during the dry season. Samples from only three of the four sampling dates at the San Diego River site, four of the eight sampling dates at the Alvarado Creek site, and seven of the eight sampling dates at the Forester Channel site produced caffeine and sucralose concentrations that met QC requirements for the internal standard (between 70% and 130% recovery); only the data from these samples were used for statistical analyses.

Humans generate between 0.7 and 1.7 kg of excreta each day, containing 50–87 g of total solids, 8–16 g of total nitrogen, and 1–4 g of total phosphorus (Hansen and Tjell, 1979; Feachem *et al.*, 1983; Schouw *et al.*, 2002; Mihelcic *et al.*, 2011). Nearly 90% of excreted nitrogen and approximately two-thirds of excreted phosphorus is in the urine, with the remainder originating from feces, though this is highly dependent on diet (Mihelcic *et al.*, 2011). Humans also generally excrete between 10^8 and 10^{11} MPN of *E. coli* and between 10^7 and 10^{10} MPN of fecal enterococci per day (Harwood *et al.*, 2017), but there are also many other animal sources of these microbial pollutants, including dogs and ducks. Therefore, if human excreta were a major source of pollution from the encampment sites, it would have been natural to also see significant increases in the concentrations of TDS, DOC, and TDN. If detergents or other soaps were used at the encampments, then we would expect to see an increase in the concentration of other constituents, such as phosphate and DOC, but this was not the case.

Dilution factors may have made it difficult to detect differences in chemical constituents, and future studies of this nature should take into account the detection limits of different analyses when calculating the number of samples to collect and the sites to choose. Thus, based on the lack of detectable levels of HF183, the low caffeine/sucralose ratios observed, and the lack of consistent, significant changes in the measured concentrations of physical-chemical pollutants associated with feces, there is not enough evidence to suggest that the homeless encampments were contributing fecal pollution to these water bodies during dry weather conditions.

Findings from interviews with service providers and key informants

Interviews with key informants from local government revealed a concern for the feasibility of providing water and sanitation services for the unsheltered population. Overall,

there was a preference against the use of portable bathrooms, such as the ones that were installed throughout the county during the Hepatitis A outbreak in 2017. The major challenges reported were related to maintenance and security. Specifically, interviewees perceived that some individuals would utilize portable toilets for illegal activities such as drug use and prostitution, unless they were monitored 24/7 by private security, which was perceived as an unfeasible expense.

Interviewees were generally aware of alternative designs for public toilets, such as the “Portland Loo,” which has features that are intended to deter certain activities, such as: slatted exterior walls to allow law enforcement officials to see when more than one person is inside; exterior sinks to discourage the use of the bathrooms for showering; and interior blue lighting to discourage intravenous drug use (Hochbaum, 2019). However, our interviews revealed perceptions that these toilets would either not effectively solve the problem or were too expensive in general. Several interviewees cited the failure of a pilot-scale project, where several Portland Loos were installed in downtown San Diego. One public sector interviewee also reported a failed attempt at using a pay-per-use system to access public toilet facilities, with reported perceptions that homeless individuals would cheat the system (e.g., by using objects as door stoppers to enter without paying).

Overall, key public sector service providers mostly agreed that the main challenge was the cost associated with the regulation and patrol of public toilets, to prevent their misuse, as well as maintenance expenditures associated with cleaning and repairing public toilet facilities that are misused or vandalized. There was a perception that these costs would be unaffordable for most cities without diverting funds away from public safety (police and fire-rescue), which accounts for the majority of the operating budget for most cities.

City authorities—particularly cities in California—are now using ever more creative tactics to displace and make unhoused people appear more invisible, to the detriment of their health and safety (Stuart, 2015; Speer, 2016, 2017). For example, during the Hepatitis A crisis last year, county and city authorities failed to fully implement hygiene measures for individuals experiencing homelessness related to hand-washing stations and restroom access until 3 months after initial discussions, and only after a directive order was issued (Howle, 2018). Further, the City of San Diego enacted a harsh regime of tickets and arrests to displace the hundreds of unhoused people living on the streets of downtown San Diego, many of whom it is suspected may have relocated to along the San Diego River, among other locations (Welsh and Abdel-Samad, 2018).

This Hepatitis A related police displacement and other cycles of police harassment have driven people into the riverbank, and further away from the service providers they often slept near in urban neighborhoods (Flanigan and Welsh, 2020). Key informants from a local river protection nonprofit organization have reported a 500% increase in encampments along the San Diego River since the onset of the COVID-19 pandemic, suggesting that pandemic-related efforts to move individuals into large temporary shelters, and the continued criminalization of homelessness by police, are causing some individuals to choose the river margins as a preferable alternative.

Our interviews with nonprofit service providers revealed that no organizations regularly provided services to people staying along the river margins as a primary target

population, though, since the time of our interviews, at least one nonprofit organization has begun outreach in that locale. Some organizations provided services on a one-off or occasional basis or assumed that some of their services recipients lived along the river margins based on their appearance (e.g., twigs in hair or other signs of living in a natural environment). Staff explained this lack of outreach as being driven by concerns for staff safety and resource constraints.

All staff members interviewed described safety concerns related to working along the river margins. Some of these concerns stemmed simply from the rough terrain that must be covered when conducting outreach in these locations, which would require substantial time and effort to assist a staff member who, for example, sprained an ankle deep in the riparian environment. Staff expressed other concerns related to the nature of the population living along the river margins.

Some staff members characterized the riverbank population in two categories. One group comprised individuals who genuinely preferred the riverbank; these residents were able to create elaborate encampments along the river margins that they could not have created in the typical built environment, for example with semi-permanent structures and furniture. The other category had been “pushed” into the riverbank by the policing activities described earlier, and staff described this group as “irate.” Staff from an environmental organization that had long worked along the riverbank and who had ongoing relationships with many riverbank residents shared that police activity had increased tensions, and newer volunteers unfamiliar to residents sometimes felt unsafe.

Key informants from nonprofit organizations reported a perception that substance abuse was more common for individuals residing near rivers and postulated anecdotally that river dwellers may be more likely to suffer from substance abuse or mental health concerns. This perception was shared by many individuals experiencing homelessness who were afraid to live along the riverbank (Flanigan and Welsh, 2020). Whether individuals preferred the riverbank or had been pushed there, staff perceived that riverbank residents likely preferred to remain unfound and were unlikely to welcome staff contact.

Service providers also reported that the attitudes of riverbank-dwelling individuals toward contact with service providers were highly influenced by their experiences and interactions with law enforcement. For example, one key informant mentioned that their interactions with river-dwelling homeless individuals in City A had “a different feel than” City B since river-dwelling homeless individuals in City A were “a little more hostile and a bit more caught off guard” due to less frequent police presence in City B.

Staff also reported that resource constraints were a major obstacle to outreach along the river margins. Many individuals experiencing homelessness accept services only after numerous repeat encounters, and this number and frequency of encounters is difficult to facilitate in the riverbank. The challenging terrain and comparatively remote locations of many encampments necessitate sending staff in pairs, posing an additional drain on limited staff. One service provider expressed concern with the fact that the river dwelling population is more likely to be chronically homeless, a claim also supported by our data from individuals experiencing homelessness (Flanigan and Welsh, 2020).

Effectively providing services to people experiencing chronic homelessness is challenging and resource intensive,

even in built urban environments. These demands, combined with already overstretched homelessness services providers and a perception that riverbank residents were service avoidant, meant that most staff estimated that outreach along the river margins was a poor investment of already limited resources.

Water, sanitation, and hygiene services for individuals experiencing homelessness are offered by several service providers in San Diego, for example, through mobile shower systems (Williams, 2018). However, findings from our interviews indicate that these services may not effectively reach the river-dwelling population, who might have a lack of trust with local authorities and may be equally as reluctant to come into contact with service providers. A lack of trust in service providers and the absence of stakeholder involvement in service provision has been previously associated with poor sustainability of water, sanitation, and hygiene programs (Jimenez-Redal *et al.*, 2018; Madon *et al.*, 2018).

Therefore, if the riverbank-dwelling transient population prefers being outside of the public view, with limited contact with service providers, then they might be more likely to utilize and sustain water, sanitation, and hygiene services that are operated and managed by them, with limited involvement from service providers (public or nonprofit). Alternatively, plans to provide water, sanitation, and hygiene services that can be accessed by this population would first require a considerable investment to build a relationship of trust between individuals residing in riverbank encampments and service providers.

Limitations

There are several limitations associated with this study that should be acknowledged. First, the relatively small sample size for the water quality analyses (e.g., $N=20$ paired upstream and downstream samples across three sites) means that there is potential that the underlying variability in the measured parameters from sample to sample could affect the conclusions from this work. As with any study performed in the field, it is not possible to completely control all environmental and external variables as would be possible in a laboratory-controlled experiment. We chose the sample size of $N=20$ based on a power calculation ($\alpha=0.05$, $\beta=0.20$), as described earlier. However, deviations from normality in the distribution of the data could lead to misleading results from the parametric hypothesis tests used.

In addition, the relatively small number of service providers interviewed ($N=7$) may have limited our ability to achieve informational redundancy or confirm the saturation of ideas or themes (Vasileiou *et al.*, 2018). For example, Hennink *et al.* (2017) interviewed HIV patients to determine what factors influenced patient retention, and they reported that code saturation was reached after only nine interviews (i.e., they had “heard it all”); however, it took 16–24 interviews to reach meaning saturation (i.e., they “understood it all”). Guest *et al.* (2006), however, concluded that thematic exhaustion was reached between 6 and 12 interviews. The required sample size for thematic saturation in qualitative research is likely dependent on the characteristics of the study, the type of information collected, and the researchers involved in the study. We interviewed seven participants for this study; however, it should be noted that additional themes or ideas could have potentially emerged if more interviews were conducted.

Conclusions

The results of this study revealed that the San Diego River and two of its tributaries contained general and human-associated fecal pollutants at low levels during dry season conditions, which may pose a risk to the health of individuals staying in riverbank encampments. However, there was no strong evidence that the encampments were causing significant increases in the concentration of fecal pollutants during dry weather conditions.

Interviews with local public sector and nonprofit sector service providers revealed a common perception that the provision of water, sanitation, and hygiene services for riverbank residents experiencing homelessness was cost-prohibitive. Public sector interviewees suggested that investing in the provision of services for this population would require reducing funds currently allocated to public safety. They further perceived that allowing homeless individuals to utilize public facilities would create public safety concerns for other tax-paying residents. On the other hand, nonprofit service providers reported that riverbank-dwelling individuals were more likely to be experiencing chronic homelessness, and less likely to be welcoming of staff contact. This led to their perception that outreach to this population was a poor investment of limited resources, given the challenging terrain and comparatively remote locations of riverbank encampments.

We recommend that improved water supply, sanitation, and hygiene facilities be provided for all individuals experiencing homelessness in river margins. This will require creative community-based participatory approach, to design water, sanitation, and hygiene technologies and services that meet the needs of this unique situation. The results of this study demonstrate that these services are needed in riverbank encampments, but the provision of these services is currently perceived by public and nonprofit sector service providers to be cost-prohibitive.

Authors' Contributions

Author contributions were as follows, based on the CRediT system taxonomy (Brand *et al.*, 2015): Conceptualization of the study, funding acquisition, and project administration was led by N.M., with support from M.E.V., S.F., M.W., A.M.K., and R.G. Laboratory method development was led by N.M. (physical–chemical water quality, sample extractions), M.E.V. (ddPCR), A.M.K. (flow rate measurement and geographic information system work), and R.G. (caffeine/sucralose analysis). Development of interview protocols, methodology, and analysis of interview data was led by S.F. and M.W. Statistical analysis of water quality data was done by M.E.V. and N.M. Field work and laboratory experimental work was led by J.S.C., M.G., and F.P. M.E.V., S.F., M.W., and M.G. wrote the original draft of the article, and all other co-authors reviewed and edited the article. M.E.V. prepared the visualizations. J.S.C. and M.G. were advised by M.E.V., and F.P. was advised by N.M.

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