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Assessing the defecation practices of unsheltered individuals and their contributions to microbial water quality in an arid, urban watershed

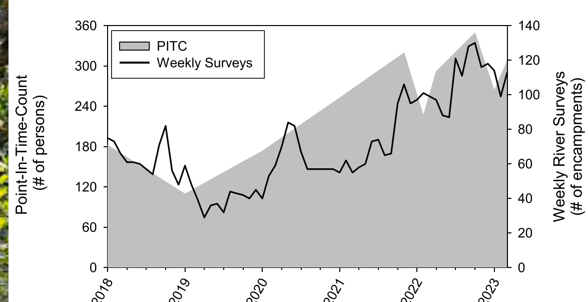
J.B. Hinds[a], Teevrat Garg[c], Sarah Hutmacher[b], Andrew Nguyen[a], Zhongqi Zheng[a], John Griffith[d], Joshua Steele[d], Adriana González Fernández[d], Kenneth Schiff[d,*]

[a] Department of Urban Studies and Planning, University of California San Diego, La Jolla, CA, USA
[b] San Diego River Park Foundation, San Diego, CA, USA
[c] School of Global Policy and Strategy, University of California San Diego, La Jolla, CA, USA
[d] Southern California Coastal Water Research Project, Costa Mesa, CA, USA

HIGHLIGHTS

- Studies quantifying homelessness contributions to water quality are rare.
- Multiple counts of unhoused individuals over 4 years.
- Surveys of sanitary habits indicated widespread open defecation.
- A large majority of unhoused contained their defecation in buckets or burial.
- Homelessness HF183 contributions were a fraction of the total watershed load.

GRAPHICAL ABSTRACT



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ABSTRACT

Outdoor defecation by people experiencing homelessness is frequently perceived as a potentially large source of human fecal pollution and a significant source of health risk in urban waterbodies with recreational contact. The goal of this study was to count the number of people experiencing homelessness and quantifies their sanitation habits in an urban river corridor setting, then use this information for estimating human fecal pollutant loading on a watershed scale. Two types of census counts were conducted including periodic point-in-time counts over six years and weekly counts of encampments. While the population census varied from count-to-count, the range of population estimates in the river corridor varied from 109 to 349 individuals during the six-year span, which mirrored the weekly counts of encampments. A face-to-face survey of people experiencing homelessness assessed the sanitation habits of the unsheltered population (N = 63), including outdoor defecation frequency and containment practices. Overall, 95 % of survey respondents reported defecating outdoors; 36 % practiced outdoor defecation between 4 and 7 days/week and 27 % practiced outdoor defecation <1 day/week. Of those that did practice outdoor defecation, 75 % contained their feces in a bucket or bag, thereby limiting fecal material contributions to the river; 6.7 % reported defecating on low ground near the river that could wash off when flood waters rise during a storm event. Only a single survey respondent reported defecating directly into the river.

* Corresponding author at: 3535 Harbor Blvd, Suite 110, Costa Mesa, CA 92626, USA.
E-mail address: kens@sccwrp.org (K. Schiff).

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Based on literature values for average HF183 output for an adult human, and the average rainfall in the urban watershed, the total watershed contribution of HF183 averaged 1.2×10^{10} gene copies per storm event (95 % CI: 0.9×10^{10}–1.6×10^{10}) along the 41 km stretch of river in this study. This human fecal loading estimate is at least two orders of magnitude less than cumulative HF183 loading from all human sources measured at the bottom of the watershed.

1. Introduction

Fecal indicator bacteria such as *E. coli* or *Enterococcus* in storm drain discharges are one of the most ubiquitous and most difficult to control pollutants of concern for watershed managers across the United States (Noble et al., 2003; Parker et al., 2010; Sauer et al., 2011). For example, there are 2250 waterbodies on the State of California's list of impaired waterbodies for fecal indicator bacteria or related pollutants (SWRCB, 2022). Finding and stopping the sources of fecal indicator bacteria contamination is especially challenging during wet weather when fecal indicator bacteria sources commingle dynamically as they flow towards the beach, where studies have observed an increased risk of illness in swimmers and surfers (e.g., Prüss, 1998; Wade et al., 2003; Colford et al., 2007; Wade et al., 2010; Arnold et al., 2017). The challenge of identifying fecal pollution sources is particularly pronounced in separate sanitary sewer and municipal storm sewer systems, which are common in most arid southwest cities (Tiefenthaler et al., 2011; Griffith et al., 2010; Noble et al., 2006; Schiff and Kinney, 2001).

One factor contributing to the challenge of finding sources of fecal indicator bacteria in wet weather is that *E. coli* or *Enterococcus* can be shed by any warm-blooded animal and may even grow in temperate to tropical ecosystems (Jiang et al., 2007; Lu et al., 2013; Ervin et al., 2014; Olapade et al., 2006; Mote et al., 2012). Quantitative microbial risk assessments have identified human fecal sources as posing the greatest risk of generating water contact recreation illness (Boehm and Soller, 2011, Harwood et al., 2014, Soller et al., 2014, Soller et al., 2015), significantly greater than non-human sources typically found in urban stormwater.

To overcome the challenge of commingled human and non-human sources of fecal pollution, source tracking investigators have utilized a human source tracking indicator: HF183, a highly conserved gene sequence in *Bacteroidales* (Bernhard and Field, 2000; Griffith et al., 2003; Haugland et al., 2010; Layton et al., 2013). HF183 is an abundant human gut microbe and, of the many microbial source tracking studies in the literature, HF183 offers one of the highest levels of precision and sensitivity for identifying human fecal pollution (Boehm et al., 2013; Layton et al., 2013).

Persistent populations of individuals living in unsheltered conditions have been perceived as a potentially large source of fecal pollution in urban stream systems (San Diego Region Bacteria TMDL Cost Benefit Analysis Steering Committee, 2017). While the potential for contamination through direct deposition of feces into waterbodies or from overland transport during wet weather is readily hypothesized, few studies have attempted to rigorously quantify this human fecal source (Verbyla et al., 2021). Potential exists for the use of advanced computing techniques and remote sensing to identify upstream contributions to fecal loading, but these approaches primarily concern contributions from larger settlements along surface waters, rather than contributions from individuals or small groups living in transient and unsheltered conditions (Hamilton et al., 2018). Characterizing outdoor defecation as a pollution source is further complicated by the transient nature of unsheltered populations, which often move based on seasonal flooding, changing vegetation, and unpredictable enforcement and land management decisions by property owners and public officials. Furthermore, gathering statistically valid information on the personal sanitation habits of unsheltered people is hampered by the distrust of surveyed individuals in a population that frequently experiences difficult interactions with authorities and the overall stigma associated with homelessness (Koegel et al., 1988).

The goal of this study was to count the number of people experiencing homelessness and quantify their sanitation habits in an urban setting, then use this information for estimating the human fecal pollutant loading from this source on a watershed scale. Human fecal pollutant loading estimates were based on mass contributions of HF183. While the human fecal loading estimates are watershed specific, this new approach and the challenges it overcomes can be recreated in any watershed.

2. Materials and methods

2.1. Setting

This study was conducted in the 419 km^2 lower San Diego River Watershed (SDR) (Fig. 1), a location with a persistent population of individuals living in unsheltered conditions in the floodplain of the river, from the crossing of CA Route 67 in unincorporated San Diego County at the east, through the City of Santee, to the mouth of the river at the Pacific Ocean at Ocean Beach in the City of San Diego. Roughly 28 % of the lower watershed is in park and recreation use, with the remainder a mix of developed land uses. This waterbody is subject to a Total Maximum Daily Load (TMDL) based on exceedances of fecal indicator bacteria water quality standards (RWQCB, 2010).

Average annual rainfall in the watershed ranges from 26.2 cm near the coast to 27.7 cm to the east. Most of this rainfall occurs between October and April, with the greatest precipitation occurring in February and March. Flows at the USGS (United States Geological Survey) gaging station at Fashion Valley – the most downstream on the SDR (river km 10) - can increase from <0.03 m^{3}s^{-1} to >300 m^{3}s^{-1} in less than a day when storms occur. There are no major dams in this section of the SDR.

While the lower watershed is roughly 52 % developed, the river channel remains predominantly unlined and the vast majority of the river corridor has riparian habitat of varying quality. The riparian corridor along this urban river provides opportunities for people experiencing homelessness to create encampments.

2.2. Census of unhoused individuals

A detailed count of unhoused persons was conducted four times within the 2021–2022 winter season. The four census events specific to this project were conducted November 4 through 7, 2021; February 24, 2022; March 31 through April 2, 2021; and September 29 through October 2, 2022. The February 2022 census was conducted as part of the national point-in-time-count (PITC), coordinated by the San Diego Regional Task Force on Homelessness (RTFH), and on the same day as the United States Department of Housing and Urban Development (HUD) national PITC. Additional PITCs used by this study were collected by the San Diego River Park Foundation (SDRPF) in coordination with the RTFH during January or February 2016–2021.

All census events for unhoused individuals followed similar methods consistent with the national and RTFH PITC (https://www.rtfhsd.org/reports-data/). For the current study, census teams deployed between 5:45 and 9:00 AM and enumerated all individuals along small river reaches using a mobile application. Consecutive river reaches were censused by multiple teams to get an entire count of the unhoused population along the lower river corridor. To translate encampments where not every individual can be observed into an estimate of the total population of unsheltered persons present, population multipliers established in 2018 by the RTFH are used to generate the estimated number of individuals per encampment point. These multipliers, which are considered by RTFH to be conservative, estimate 1.75 persons per hand-built shelter (such as a tent or other structure), and 2.03 persons per inhabited vehicle (Regional Task Force on Homelessness, 2020).

The primary difference between national and RTFH PITCs and the study specific PITC relates to timing: National PITC data are collected in a single day, while study-specific PITC data were conducted over four consecutive days. In addition, information such as name, sex, race, or other personally identifying demographics were not collected by this study as is the case in the national PITC.

In addition to the PITC census events, encampment points have been surveyed weekly since 2018 to capture the dynamic nature of encampment locations over time. These weekly encampment surveys consist of teams of SDRPF staff and volunteers, who cover one to four river segments each day. During the weekly encampment point surveys, locations of encampments are geocoded and the nature of the encampment is noted (i.e., a description of encampment contents). Each encampment location may include multiple structures and individuals.

2.3. Survey of sanitary habits

The sanitary habits survey comprised 10 questions designed to quantify the frequency of outdoor defecation, containment practices, disposal practices, and the proximity of any direct defecation or deposition of feces to the San Diego River. The survey instrument can be found in Supplemental Material A.

Subjects were recruited on 25 discrete days between December 10, 2021, and April 14, 2022, coinciding with the winter season census data collection. A pilot survey in December 2021 was utilized to test and validate the survey instrument. Recruitment criteria included individuals ≥18 years of age and living in the river corridor; informed consent was required from every individual prior to being surveyed. Recruitment occurred during daylight hours, typically in the morning between 8:00 AM and noon. The University of California Human Subjects Institutional Review Board reviewed the study and all procedures were performed in compliance with institutional guidelines (IRB# 800758).

The survey was administered using the Survey123 platform on mobile phones by professional outreach specialists employed by People Assisting the Homeless (PATH), a non-profit organization providing comprehensive services to prevent and reduce homelessness (www.epath.org). PATH staff members are authorized to make contact with individuals throughout the County, including the SDR corridor, and conduct regular work in the river corridor with SDRPF staff. A unique code identifier was used for each enrolled subject so that anonymity could be maintained yet ensure individuals were not interviewed twice.

A $10 gift card was offered as an incentive for individuals to enroll and complete the survey, consistent with compensation offered in other social science research conducted with unsheltered individuals (Lewis et al., 2022).

The survey allowed respondents to answer for themselves or “for someone they know” to help prevent reporting bias (Tourangeau and Yan, 2007). A Likert scale was used to quantify behaviors such as the frequency of defecation. The option to record open-ended responses and comments was incorporated into the survey and Survey123 application design. Finally, the Survey123 application incorporated a georeferenced mapping feature allowing survey administrators to geocode the location where the survey was taken and for individuals to point to the location of any designated latrines or feces disposal sites. The application included the boundaries of the 100-year and 500-year floodplains, which were used to categorize respondents' defecation, containment and disposal sites as “towards the river” and “away from the river.”

A total of 68 individuals were approached for survey recruitment. Of these, 63 (93 %) individuals successfully completed the survey or an

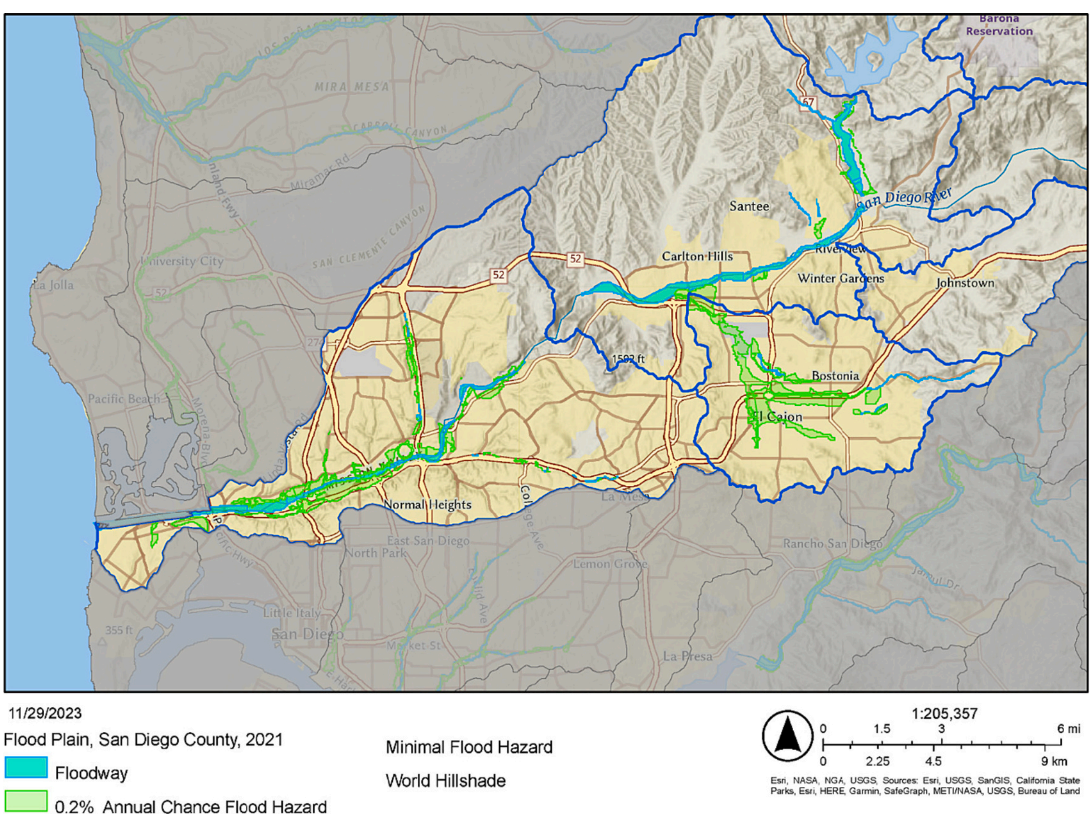

Fig. 1. Map of the lower San Diego River watershed. Census events, encampment reconnaissance, and survey recruitment occurred largely within the San Diego River Floodway with 0.2 % Annual Flood Hazard Zones.

average of 25 % (95 % CI: 22–30 %) of the censused population. All but two of the individuals recruited were surveyed while physically present at a site within the river corridor; the two individuals were known to live within the river corridor and provided information specific to their defecation habits during periods when they were living within the river corridor (Fig. 1).

Any survey is susceptible to recruitment and response bias. Recruitment bias was presumed low due to the high recruitment rates. Response bias was unquantified, but presumed low, based on the ongoing and trusted relationships with recruitment staff. Sensitivity analysis was conducted to ascertain if bias could alter the final conclusions (see Section 2.4). The survey was designed to ask a series of binary questions (yes/no) or multiple-choice questions that can be transformed into an array of binary questions. Based on the variance from survey responses in early waves of data collection and an original estimated total population size of 320 individuals in the standard survey area, using RTFH multipliers and data from the November 2021 census, a minimum sample size of 59 completed surveys was targeted to yield 95 % confidence with a 2 % error tolerance. In cases where subsets of responses were used, sample sizes provided adequate power to generate 95 % confidence intervals on subsets of all responses with a modestly higher error tolerance (5 %).

2.4. Theory and calculations of HF183 load

The inputs of human fecal contamination from people experiencing homelessness were defined as mass load of HF183 (sum gene copies). This estimate was calculated according to Eq. (1):

$$M = S^*\sum_{n=1}^{3}((N^*Pd^*Dd^*W^*M^*C) + (N^*Pi^*Di^*W^*M^*C)) \quad (1)$$

where:

M = best estimate of average annual mass loading HF183 from people experiencing homelessness
S = average number of storms per year
n = number of days preceding storm event
N = number of people experiencing homelessness
P_d = proportion of people experiencing homelessness with direct deposition
D_d = decay rate of HF183 for in-water deposition
P_i = proportion of people experiencing homelessness with indirect deposition
D_i = decay rate of HF 183 for deposition on stream banks that can later wash off into the river when floodwaters rise
W = weighted average defecation frequency
M = mass of fecal material per person per day
C = concentration of HF183 gene copies per gram feces wet weight.

San Diego has averaged 10 storms per year over the last 10 years. The average number of people experiencing homelessness was 245 (95 % CI: 208–282) derived from the census data collected during the study. The proportion of people experiencing homelessness with direct (0.02) or uncontained indirect (0.15) deposition of defecation was derived from the survey data collected during this study. The average frequency of defecation was weighted by proportion of people defecating per number of days per week based on survey data collected during this study. Because the survey size gets uncomfortably small for differentiating direct versus indirect defecation by frequency of defecation, the weighted average frequency of defecation was applied across both direct and indirect deposition populations. Decay rates for HF183 were locally derived from treated wastewater under full to partial sunlight and wintertime temperatures (Cao et al., 2017). Decay rates for direct deposition were estimated to be 0.5/day and decay rates for indirect deposition were 0.9/day. In all cases, 100 % decay of HF183 was assumed after three days (Cao et al., 2017; Mattioli et al., 2017). An estimated 125 g feces per person per day was derived from Rose et al. (2015). A geomean concentration of $1 \times 10^{6.67}$ HF183 gene copies per gram feces (95 % CI: $1 \times 10^{6.61}$–$1 \times 10^{6.72}$) was derived from Seurinck et al. (2005). The geomean HF183 concentration per gram feces was calculated using a two-step monte carlo process. The first step of the process identified if a fecal sample would be detectable or non-detectable for HF183 based on the binomial distribution calculated from Seurinck et al. (2005). If non-detectable, then the HF183 concentration was assumed to be zero. If positive, then the second step estimated the HF183 concentration based on a random concentration from lognormal distribution calculated from the detectable samples in Seurinck et al. (2005). This two-step monte carlo simulation utilized 10,000 iterations. See Supplemental Material B for a definition of each parameter in the model and the details of the two-step monte carlo simulation for HF183 concentration per mass feces.

Sensitivity analysis was conducted to evaluate the effect of the various model parameters and assumptions about mass loading. The "best estimate" of human fecal loading is based on averages of model parameters such as number of people experiencing homelessness, HF183 concentrations per gram feces, and defecation frequency. Sensitivity analysis independently increased the value of defecation frequency to daily, removed bacterial decay, increased to the maximum number of people experiencing homelessness during the census periods, assumed all persons practiced direct defecation, or increased the HF183 concentration per gram feces to the maximum in the literature.

3. Results

3.1. Census results

The census enumerated between 225 and 349 people experiencing homelessness in the SDR corridor across the four census events during the 2021–22 wet season (Fig. 2). This range of census values is only marginally greater than the range of people experiencing homelessness from the annual PITC in the previous 3 years, between 2018 and 2020, which ranged between 109 and 248. In general, both censuses indicated higher numbers of unhoused in 2022 than in 2020 or 2021. Across all PITC census events, the average number of unhoused living in the SDR corridor is 245 (95 % CI: 208–282).

The difference in census values from wintertime PITCs between 2018 and 2020 and the winter of 2021–22 do not appear to be biased based on independently collected data sets (Fig. 2). Counts of encampments, while not counts of individuals, are a good surrogate for population size and correspond well with the increases observed in 2021–22. Encampments generally increased when PITCs increased, with the lowest number of encampments in 2019 and the greatest number of encampments in 2021. Thus, the weekly encampment counts illustrated that PITCs did not miss large variations in homeless populations.

3.2. Survey results

A total of 95.2 % of respondents (N = 63) stated that they or someone they know defecates outdoors; three respondents stated that they do not ever defecate outdoors in the riverbed and do not know of anyone who does (Table 1).

Frequent defecation, defined as 4 or more days per week, accounted for 36.4 % of the respondents (Table 1). Infrequent defecation, defined as 1 to 3 days per week, accounted for 36.5 % of the respondents. The remaining respondents (27.1 %) indicated they do not defecate outdoors or do so "only when I have to".

The majority of survey respondents (75.0 %) indicated using a bucket or bag for containing their defecation (Table 1). Additionally, 58.3 % of respondents indicated they buried their defecation; some of these respondents might also use a bucket or bag at other times. Regardless, a much smaller proportion of respondents (6.7 %) indicated that they did not use containment and may defecate on open ground.

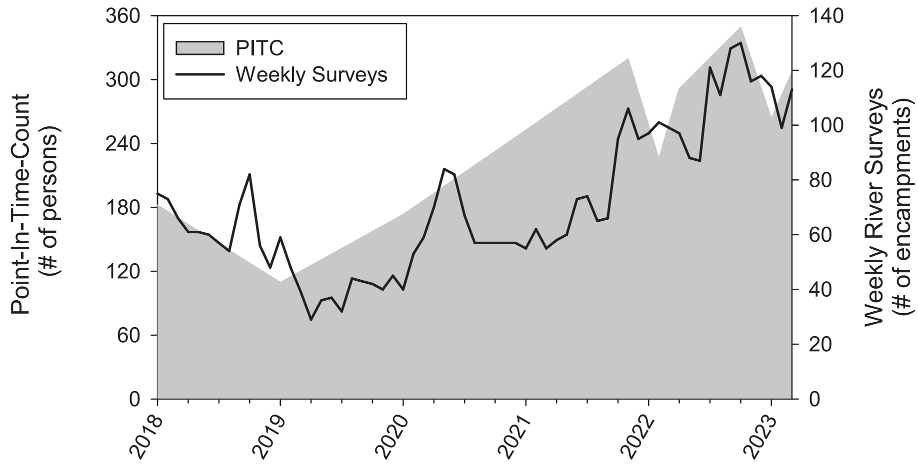

Fig. 2. Average number of active encampment locations by month, 2018–2022 during ongoing surveys (line plot first y-axis) and estimate of unsheltered population from census events (area plot second y-axis).

Table 1
Survey results of defecation habits among people experiencing homelessness along the San Diego River corridor.

Defecate outdoors?	Percent of respondents (N = 63)	Weekly defecation frequency	Percent of respondents (N = 63)	Defecation containment	Percent[a] of respondents (N = 60)	Location of container disposal	Percent of respondents (N = 52)
Yes	95.2	7 days	22.2	Bucket or bag	75.0	Trash	75.0
No	4.8	6–7 days	7.9	Bury	58.3	Bury	7.7
		4–5 days	6.3	No Containment	6.7	On high ground	3.8
		2–3 days	19.0			On low ground	0
		1–2 days	17.5			In river	0
		Only when have to	22.2			On ground, location not specified	1.9
		Do not defecate outdoors	4.8			Other disposal, location not specified	11.5

[a] Respondents may select more than one option, so adds to >100 %.

This pattern of containment and disposal appeared similar between respondents who defecated frequently and those that defecated infrequently along the SDR corridor (Table 2). Thus, we did not use containment or containment disposal versus defecation frequency as a factor for estimating total human fecal pollutant mass loading.

Table 2
Count of survey respondents on use and disposal of containers (Buckets or Bags).

	Frequent Defecation (N = 23)	%	Infrequent Defecation (N = 37)	%
Percent indicating use of bucket or bag at least sometimes, based on response to Question 7 (i.e., response was not "other," "it depends," or no response)	18	78.3 %	29	78.4 %
Question 8: If you/they use a bucket/bag(s), it is MOST OFTEN thrown out or emptied:				
Trash/dumpster	14	60.9 %	26	70.3 %
Bag is buried (from comments)	2	8.7 %	2	5.4 %
Disposal on the ground, away from the River	1	4.3 %	1	2.7 %
Disposal on ground, location not specified	1	4.3 %	0	0.0 %
Disposal on ground, towards the River	0	0.0 %	0	0.0 %
Disposal in River	0	0.0 %	0	0.0 %

Of respondents that utilized containment in a bucket or bag, the vast majority (75.0 %) throw the container in the trash (Table 1). A much smaller proportion bury the waste (7.7 %), dispose on the ground above the 100-year flood plain (3.8 %), or dispose on the ground in an unspecified location (1.9 %). No respondent described disposing the contained waste in the river. When these data are broken down by frequency of defecation outdoors, these patterns continued to hold (Table 2); a slightly smaller proportion of frequent defecators reported throwing the containment in the trash (60.9 % versus 70.3 % of infrequent defecators), and a slightly greater proportion of frequent defecators reported burying or ground disposal (17.3 % versus 8.1 %).

3.3. Fecal loading estimates

The census and survey data indicate that an average 1.2×10^{10} HF183 gene copies (95 % CI: 0.9×10^{10}–1.6×10^{10} HF183 gene copies) are discharged to the 41 km SDR river corridor from people experiencing homelessness during a typical storm event (Fig. 3). With an average of 10 storm events per year in the SDR watershed, the best estimate of annual wet weather loading from people experiencing homelessness is 1.2×10^{11} HF183 gene copies.

Sensitivity analysis indicates HF183 concentrations per mass feces is the most important variable when estimating human fecal loading from people experiencing homelessness when using the model (Fig. 3). Concentrations of HF183 in the literature (Seurinck et al., 2005; Layton et al., 2013; Ahmed et al., 2019) range four orders of magnitude – from 10^5 to 10^9 gene copies/g wet feces - whereas ranges for the other model parameters are at most an order of magnitude and often less. Worst case assumptions for HF183 concentration per mass feces increases the fecal

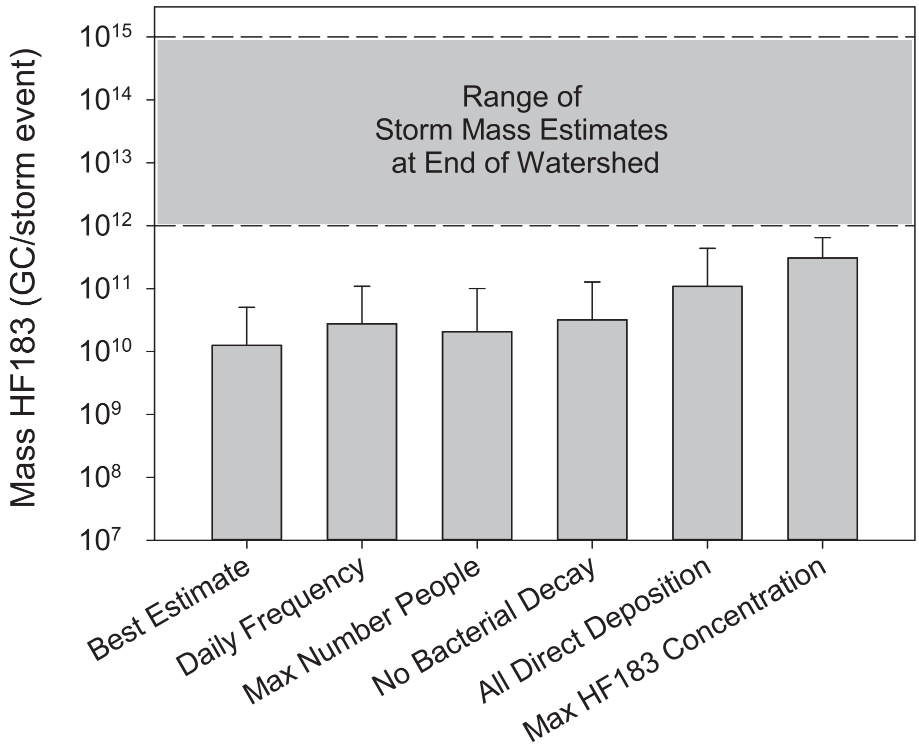

Fig. 3. Estimates of HF183 mass loading per storm event from people experiencing homelessness in the San Diego River corridor based on this study's best estimate, and the increase in mass based on maximizing conservative assumptions (including increasing defecation frequency to daily, removing bacterial decay, increasing the number of people experiencing homelessness to the maximum census event, assuming all people experiencing homelessness directly defecate into the San Diego River, or using the maximum HF183 concentration per gram feces reported in the literature). Each of these assumptions do not approach the range of HF183 mass measured at the end of the San Diego River watershed during seven storm events in 2010–2012.

loading from an average 10^{10} gene copies per storm event to a maximum of 10^{11} HF183 gene copies. In contrast, increasing each of the other model parameters - the number of people experiencing homelessness to the maximum census value, removing any bacterial decay, or assuming all unhoused persons directly defecate into the river – increase the human fecal loading at most to 10^{10} HF183 gene copies per storm event.

Despite these estimates of uncertainty, human fecal mass loading from people experiencing homelessness appears small relative to total watershed loading. In this paper, we estimate that HF183 loading from people experiencing homelessness averages 1.2×10^{10} gene copies per storm event. Steele et al. (2018) estimated HF183 loading at the end of the lower San Diego River watershed at 10^{12}–10^{15} GC per storm event across seven different events between 2010 and 2012. Thus, the end-of-watershed HF183 loading is at least two orders of magnitude greater than our estimate of loading from people experiencing homelessness.

4. Discussion

To the authors' knowledge, a study combining repeated census events with a survey of sanitation habits of people experiencing homelessness is the first of its kind. There have been many census events, including the yearly national PITC over the last 10 years, but the data are reported at census block resolution to support the need for unsheltered services and to guide policies on homelessness; at this scale, national PITC census data are not usable for estimating the number of people experiencing homelessness directly along the river corridor. Surveys of sanitation habits likewise are rare (Flanigan and Welsh, 2020) and of insufficient detail for making estimates of human fecal pollution loading. This study provides proof-of-concept for other researchers estimating the human fecal loading from people experiencing homelessness in other watersheds.

Previous studies working to quantify fecal pollution loading from outdoor defecation using an upstream-downstream sampling approach (Garg et al., 2018) have encountered significant challenges during wet weather. Large upstream concentrations compared to small changes downstream, compounded by highly variable results within and between storm events, makes detecting increases in HF183 (or fecal indicator bacteria) mass around encampments difficult. These challenges are exacerbated by the temporal variability in encampment locations which are continuously in flux due to law enforcement activity, weather, the availability of services, and periodic storm-driven flooding. Based on these sources of variability, large sample sizes would be necessary to detect small differences and in arid climates like the SDR may take many years.

The mass estimates of human fecal pollution from people experiencing homelessness to the lower San Diego River averaged 1.2×10^{10} HF183 gene copies per storm event. However, the precision of this estimate is uncertain and could be variable due to many factors. Based on the sensitivity analysis, HF183 concentrations were the most important variable driving uncertainty. Concentrations reported in the literature range from 10^5 to 10^9 gene copies per gram human feces. Not every human sample contains HF183 genetic material, which exacerbates uncertainty; researchers have found that as much as 14 % of individual human fecal samples do not test positive for HF183 (Seurinck et al., 2005). Importantly, HF183 is both sensitive and specific for human feces, discounting concerns that HF183 may be arising from fecal sources other than humans (Bernhard and Field, 2000; Boehm et al., 2013).

A second factor that could contribute to uncertainty in the human fecal loading estimate from people experiencing homelessness is the size of the unhoused population. This study used standard techniques used nationally, but at a frequency four times that used previously. The primary purpose for increasing frequency was to ensure that major increases in population were not missed and independent data surveying the number of encampments corroborated our findings. It was unlikely a large spike in population was missed. However, one critique of the census methods was the focus on the SDR corridor, which is closest to the river and most likely to contaminate the waterway. To assess the potential undercount in population estimates, special studies attempting to census people experiencing homelessness in untraveled portions of the lower river (i.e., minor tributaries) did not reveal large increases in population numbers (roughly 10 %, data not shown). Likewise, people experiencing homelessness outside of the river corridor but still within the lower SDR watershed may contribute to fecal loading via the municipal storm sewer system. However, based on a single PITC in February 2022 when both the entire lower watershed and the river corridor were simultaneously censused, the unhoused population estimate increased by a maximum of 50 %. However, estimating the increase in fecal mass loading is difficult to predict since the sanitation habits of the unhoused population outside of the river corridor are likely different - with presumably more access to services and less open defecation - compared to those living within the river corridor.

A third factor that could contribute to uncertainty in the human fecal loading estimate from people experiencing homelessness is variation in rainfall quantity, intensity, and antecedent rainfall (Tiefenthaler et al., 2011; Ackerman and Weisberg, 2003). The SDR averages 10 storms annually, typically confined to the wet season of October through April. However, the washoff of fecal material on stream banks is not well quantified (Calderon et al., 2022). For this study we conservatively assumed that 100 % of fecal material indirectly deposited on stream banks was washed into the river every storm event. Moreover, we assumed once washed into the river 100 % of the fecal material flowed downstream to the end of the watershed during each storm event. The lower SDR is fairly short (41 km) and transport times are on the order of hours according to USGS stream gauges.

Despite these estimates of uncertainty, and the conservative assumptions used in the model, human fecal mass loading from people experiencing homelessness appears small relative to total watershed loading in the SDR estimated by Steele et al. (2018), as much as three orders of magnitude less. If we assume survey respondents might have been untruthful, we re-calculated mass emissions based on various worst-case assumptions: (a) every person defecated daily as opposed to the reported frequency of outdoor defecation, (b) all unhoused individuals directly defecated into the river and all of the survey respondents emptied their contained feces into the river rather than in the trash, or (c) that feces from each person experiencing homelessness contained the maximum concentration of HF183 per gram feces. However, even with these maximum but equally unrealistic worst-case scenarios, loadings are still a diminishingly small fraction of the load from the entire watershed. Mladenov et al. (2020) has reported additional potential human fecal pollutant sources in the lower SDR watershed. Identifying and quantifying other sources of human fecal pollutant loading such as public sewers (collection system exfiltration or overflows) and private sewers (onsite wastewater treatment systems or laterals) remains an area of ongoing research.

The relatively small inputs of human fecal pollution to the lower SDR from unhoused populations compared to the entirety of the watershed does not obviate the public health concern. Not all watersheds may be similar to the SDR and we encourage other researchers to conduct their own local investigations. But even a minor source of human fecal pollution can result in health risk at downstream swimming beaches. Relationships between HF183 and pathogens have been reasonably well documented in public sewage systems (Eftim et al., 2017). However, this relationship may not be the same for unhoused populations, especially populations in relatively low numbers such as those along the lower SDR corridor. Pathogen shedding is a function of population infection rates, and people experiencing homelessness may have a smaller or larger infection rate than the housed population in the lower watershed.

5. Conclusions

Results from this census and survey indicate the population of people experiencing homelessness living in the lower San Diego River corridor is bounded at maximums of a few hundred and, while outdoor defecation by individuals dwelling within the lower San Diego River corridor is widespread, containment practices including using buckets or burial also are widespread. The overall prevalence of on-the-ground, uncontained outdoor defecation, which would be most likely to lead to the transport of HF183 into the San Diego River, appears to be a maximum of roughly 6.7 % of the total respondents.

Estimates of human fecal pollutant loading from people experiencing homelessness is estimated in the range of 10^{10} HF183 gene copies per storm event, but measured loads at the bottom of the watershed are orders of magnitude greater. The difference is unlikely from uncertainty in the census and survey estimates based on sensitivity analysis, thus indicating the likely presence of other human fecal sources during wet weather.

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CRediT authorship contribution statement

J.B. Hinds: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Teevrat Garg:** Writing – original draft, Methodology. **Sarah Hutmacher:** Writing – original draft, Methodology, Investigation. **Andrew Nguyen:** Software, Data curation. **Zhongqi Zheng:** Investigation. **John Griffith:** Writing – review & editing, Conceptualization. **Joshua Steele:** Writing – review & editing, Conceptualization. **Adriana González Fernández:** Visualization, Methodology, Formal analysis. **Kenneth Schiff:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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