

## Household level wastewater management and disposal data collection in the U.S.: the history, shortcomings, and future policy implications

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### ABSTRACT

Country-level sanitation access is monitored globally by the Joint Monitoring Programme (JMP). However, recent reports on sanitation access in high-income countries indicate that the JMP data may underestimate the prevalence of unsafely managed sanitation in these settings. This study explains the surveys that collect household-level wastewater management data in the U.S. and analyzes the accuracy and reliability of these data sets. From 1940 to 1990, sewage disposal data were collected comprehensively through the U.S. Decennial Census. These data are currently collected through the American Housing Survey (AHS) which appears to greatly underestimate the usage of onsite wastewater treatment systems (OWTS). In addition to these surveys, we highlight current efforts to introduce a sewage disposal question to the American Community Survey (ACS), localized efforts to collect wastewater data, and the Point-in-Time count of people experiencing homelessness. Using estimates of OWTS usage in new housing, this study provides the first defensible national estimate of OWTS usage since 1990. We estimate that 25.03% of U.S. households use OWTS which exceeds the AHS estimate (15.7%) by over 12 million households. This study discusses the potential for better wastewater data collection to inform future wastewater policy and improve the quality of life for U.S. residents.

**Key words:** Census survey questionnaires, Decentralized wastewater treatment, Environmental justice, Onsite wastewater treatment, Sustainable development goals, Wastewater access data

### HIGHLIGHTS

- The Decennial U.S. Census collected sewage disposal data until 1990 with no recent representative data.
- We estimate 32.2 million U.S. housing units (25.03%) use onsite wastewater treatment systems (OWTS) based on data from the Decennial Census and new housing.
- Accurate data are needed to inform allocation of federal funding, but current data under-represent residents without access to safely managed sanitation.

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## GRAPHICAL ABSTRACT

	U.S. Census Bureau		U.S. Department of Housing and Urban Development (HUD)		National Environmental Services Center (NESC)
	Decennial Census	American Community Survey (ACS)	American Housing Survey (AHS)	Point-in-Time Count	Assessment of U.S. Onsite System Installations
<b>Frequency</b>	every 10 years	every year	every two years	every year (in January)	2015-2018
<b>Data Type</b>	Sewage Disposal  Indoor Plumbing	Indoor Plumbing  Cost of Water and Sewer	Sewage Disposal  Indoor Plumbing	Count of people experiencing homelessness in both sheltered and unsheltered circumstances	Onsite Wastewater Treatment System (OWTS) Permits (installation, replacements/repairs)
<b>Data Subject</b>	Housing Units	Individuals/Households	Housing Units	Individuals/Households	Permits
<b>Status</b>	Collected sewage disposal data 1970-1990  Collected indoor plumbing data 1940 to 2000	Removed flush toilet from indoor plumbing facilities in 2016  Currently testing the incorporation of the sewage disposal question from the Decennial Census	Informs the Joint Monitoring Programme Data for U.S.  Underestimates the quantity of OWTS in the U.S.	Collects data on residents that are not fully counted by other surveys and who are more likely to have limited or open defecation sanitation access	Only survey to collect data on administered OWTS permits  Found 70% of OWTS permits are for new systems  Estimated 29-32% of new housing units use OWTS
<b>Limitations</b>	Out-of-date data  Combines treated and untreated sewage disposal methods as one response option	Questionnaires for group quarters do not collect indoor plumbing or cost of water and sewer data  High nonresponse rate for indoor plumbing question	Small sample size; limited inclusion of rural housing units  Combines treated and untreated sewage disposal methods as one response option	Does not collect data on sanitation access  Not incorporated in data reported to the Joint Monitoring Programme	Low response rate from some permitting agencies
<b>Study estimates that 32.2 million U.S. housing units used OWTS (25.03% of U.S. housing stock) in 2021</b>					
<b>Conclusions</b>					
<ul style="list-style-type: none"> <li>• Current data do not directly align with categories for global sanitation access monitoring</li> <li>• There is a deprioritization of collecting household-level wastewater data and an underrepresentation of historically excluded communities</li> <li>• Current data do not identify residents who need assistance in improving their access to wastewater services</li> <li>• Current funding mechanisms do not equitably distribute financial assistance to all types of wastewater treatment systems</li> <li>• Current funding mechanisms need to be expanded in scope to provide more effective financial assistance to more residents</li> </ul>					

## INTRODUCTION

By 2030, the United Nation's Sustainable Development Goal 6.2 strives to enable 'access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations' (United Nations, 2015). Currently, sanitation service access is tracked globally through the World Health Organization (WHO) and the United Nations Children's Fund's (UNICEF) Joint Monitoring Programme (JMP). The JMP uses a five-level service ladder (open defecation, unimproved, limited, basic, and safely managed) to evaluate sanitation access for countries throughout the world. Whereas many low-income countries have externally funded household surveys like the Demographics and Health Survey (DHS) or Multiple Indicator Cluster Survey (MICS) (United States Agency for International Development *et al.*, 2021), most high-income countries self-report data for the JMP (e.g., from results of a question on a national census). However, these data and corresponding survey questions do not necessarily align with the five service levels of sanitation access that are used for JMP reporting and monitoring of sanitation access. In addition to this misalignment, there are numerous other limitations present for data from high-income countries as a result of deprioritizing the collection of household-level wastewater data (Sato *et al.*, 2013; US Water Alliance and DigDeep, 2019; Maxcy-Brown *et al.*, 2021) and underrepresenting historically excluded communities (Capone *et al.*, 2020; Mattos *et al.*, 2021b; Maxcy-Brown *et al.*, 2021). It is essential to have a reliable means to collect wastewater access data for measuring the current types of wastewater management strategies,

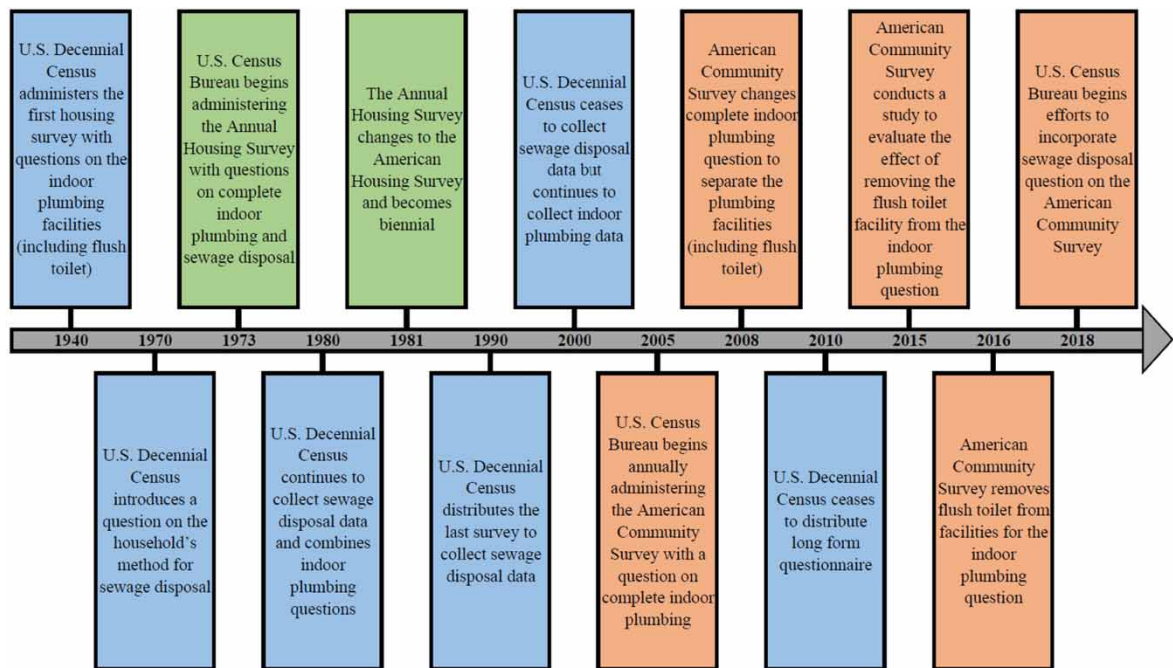
identifying households that need access improvements, and tracking progress toward achieving equitable access to safely managed sanitation.

In the United States, wastewater (or sewage disposal) access data have historically been collected through surveys administered to individuals and households by the U.S. Census Bureau. These surveys collect data on the type of sewage disposal method that housing units have access to, including public sewer, onsite wastewater treatment systems (OWTS), other means, or no system. These data are reported to JMP to determine estimates for the number of persons within each service access level. The U.S. Decennial Census long-form collected basic wastewater data until 1990 (U.S. Census Bureau, 1990, 2000). Currently, the U.S. Census Bureau collects wastewater data for U.S. residents through the American Community Survey (ACS) and the American Housing Survey (AHS). Both the ACS and AHS collect data on indoor plumbing, but only the AHS currently collects data on sewage disposal. The most recent JMP uses data from the 2019 AHS to report that 98.3% of U.S. residents have access to safely managed sanitation while 1.4% of residents have basic sanitation access and 0.3% of residents have unimproved sanitation access (about 1.1 million people) (WHO & UNICEF, 2020). Safely managed sanitation access data for the U.S. is reported for 'Total' and 'Urban' while 'Rural' is only reported as 'at least basic' (WHO & UNICEF, 2020) which indicates no capacity to differentiate between basic or safely managed sewage disposal methods in rural areas. The JMP data for the U.S. reports that there are zero residents who rely on limited service or open defecation (WHO & UNICEF, 2020). This is a misrepresentation of the sanitation situation in the U.S. because it clearly does not account for the estimated 580,000 persons experiencing homelessness each night (Department of Housing and Urban Development, 2023) who rely on shared facilities (limited sanitation access) or open defecation, nor does it include the households without at least basic wastewater management who rely on incomplete indoor plumbing (US Water Alliance and DigDeep, 2019), failing septic systems (Siddoway, 1988), straight pipes (Maxcy-Brown *et al.*, 2021), cesspools (State of Hawaii Department of Health, 2021), failing outhouses (US Water Alliance and DigDeep, 2019), and bucket latrines (Eichelberger, 2018). The scope of this paper does not include the evaluation of monitoring centralized wastewater collection and treatment systems including combined sewer overflows (CSOs), sanitary sewer overflows (SSOs), and National Pollutant Discharge Elimination System (NPDES) permit compliance.

This paper focuses on household (or individual) level data collection with the specific objectives to (1) evaluate the current surveys collecting wastewater data in the U.S. that are administered by the federal government (through the U.S. Census Bureau and the U.S. Department of Housing and Urban Development), (2) discuss other surveys that have been used to collect wastewater data in the U.S., (3) provide the first defensible estimate of nationwide OWTS use since the 1990 Census, (4) look toward the future of wastewater data collection in the U.S., and (5) inform the trajectory for future wastewater policy.

## U.S. DECENNIAL CENSUS

The U.S. Decennial Census collected data on the means of household wastewater (sewage) disposal from 1970 until 1990 (Figure 1), after which the question was removed (U.S. Census Bureau, 1990, 2000, 2021a; Maxcy-Brown *et al.*, 2021). The U.S. Decennial Census long-form (delivered to roughly 20% of U.S. households) collected nationwide information on wastewater disposal using one question (H16 in 1990, Table 1), which allowed the resident to choose three options for their wastewater management: (1) public sewer, (2) septic tank or cesspool, or (3) other means (U.S. Census Bureau, 1990). The 1990 long-form Census data are certainly useful, but they are over 30 years out-of-date and interpreting responses can be challenging. It is important to note that this question is focused on the means of wastewater disposal and not the proper functionality of the treatment system.



**Fig. 1** | Summary timeline of U.S. surveys collecting sewage disposal and indoor plumbing data.

**Table 1** | U.S. Decennial Census questions on sewage disposal (U.S. Census Bureau, 1990).

H16: Is this building connected to a public sewer?

- Yes, connected to public sewer
- No, connected to septic tank or cesspool
- No, use other means

The trends in sewage disposal between 1970 and 1990 showed a slight increase in the proportion of the U.S. population on public sewer (71.2–74.8%) while septic tank or cesspools stayed relatively steady (24.5–24.1%) and other means decreased (4.3–1.1%). In the 1990 Decennial U.S. Census, roughly 208 million residents (76.5 million households) were connected to public sewer for wastewater management (U.S. Census Bureau, 1993, 1995). There were also roughly 67 million residents (24.7 million households) who relied on septic tanks or cesspools for wastewater management and roughly 3 million residents (1.1 million households) who relied on other means (U.S. Census Bureau, 1993, 1995).

In question H16, the answer ‘connected to public sewer’ the household level data are not connected to any data on the proper disposal of wastewater after it leaves the household and is conveyed via public sewer to a centralized treatment plant. Considering the U.S.’s history of CSOs and SSOs which discharge large quantities of untreated or incompletely treated wastewater (Burian *et al.*, 2010; Potera, 2018; Botturi *et al.*, 2020; U.S. EPA, 2020, 2021a; Prevost, 2022), it is not a reasonable assumption to conclude that all households with connections to public sewer have access to safely managed sanitation even though this is often how the data are reported to

JMP. Centralized wastewater system performance is monitored through NPDES permits and state-level spill reporting but these are beyond the scope of this paper's focus on wastewater data collection at the household level.

The question H16 answer 'No, connected to septic tank or cesspool' did not clearly differentiate failing, unpermitted OWTS from functioning, permitted OWTS (Maxcy-Brown *et al.*, 2021). The questionnaire did provide a section with instructions that stated 'A septic tank or cesspool is an underground tank or pit used for disposal of sewage' (U.S. Census Bureau, 1990), but these instructions did not clarify the method for discharge from the septic tank/cesspool. It is important to note that cesspools are not designed to treat wastewater and are not recognized as treatment systems by the U.S. Environmental Protection Agency (U.S. EPA, 2021b). The answer choice only asks about the container to which the wastewater is conveyed and neither option included is able to independently treat the wastewater properly. A septic tank should be followed by a drainfield for infiltration and pathogen removal, but this question is unable to clarify if this is the case. It is likely that many with a flush toilet and no sewer connection are simply unaware of the means of sewage disposal at their residence and assume that it is a proper septic system (Nasim *et al.*, 2023).

The final option for H16 'No, use other means' was meant to capture primarily the use of outhouses, but would also include a variety of wastewater disposal methods like straight pipes, composting toilets, and honeybuckets (buckets with toilet seats attached). Any disposal method that is captured in this answer choice is likely to be considered not safely managed and a direct threat to human and environmental health. The quantity of residents relying on 'other' wastewater management strategies had decreased greatly in the decades before 1990 as outhouses were being replaced with indoor plumbing, but there are still populations today that do not have access to proper wastewater disposal.

The U.S. Decennial Census long-form collected data on indoor plumbing from 1940 to 2000 (Figure 1) after which the long-form questionnaire was excluded from the 2010 or 2020 Decennial Census and a version of question H10 (Table 2) was instead included on the ACS (U.S. Census Bureau, 2000, 2021a; Herman, 2008). From 1940 to 1970, the Decennial Census asked about each plumbing facility individually, which enabled tracking access to flush toilets in the U.S. (U.S. Census Bureau, 2021a). In 1940, flush toilet data was collected for 48 states and Washington, DC (no data for Alaska or Hawaii) and found that 12 million housing units (35.3% of U.S. housing units) did not have a flush toilet with 20 states that had over 50% of housing units lacking a flush toilet (U.S. Census Bureau, 2021a). Starting in 1950, data were collected for all 50 states and Washington, DC (U.S. Census Bureau, 2021a). By 1960, 6 million housing units were without a flush toilet (10.3%) and only 8 states had over 25% of housing units without a flush toilet (U.S. Census Bureau, 2021a). When the Decennial Census combined the plumbing facilities into one question (such as Question H10 from the 1990 Decennial Census), the data were still relevant for understanding the potential for the use of certain wastewater disposal methods that do not use a flush toilet (e.g., bucket latrines and outhouses), but it was focused on 'complete plumbing' which no longer allowed the respondent to clarify which aspect of the plumbing facility is lacking; thus, it is

**Table 2** | U.S. Decennial Census questions on indoor plumbing (U.S. Census Bureau, 1990).

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H10: Do you have COMPLETE plumbing facilities in this house, apartment, or mobile home; that is, (1) hot and cold piped water, (2) a flush toilet, and (3) a bathtub or shower?

- Yes, have all three facilities
  - No
-

impossible to determine which percentage of homes lacked a flush toilet. In 1990, there were 1.1 million housing units (1.1%) that did not have access to complete plumbing facilities (U.S. Census Bureau, 2021b).

### AMERICAN COMMUNITY SURVEY

Starting in 2005, the U.S. Census Bureau began administering the ACS annually (Figure 1). The ACS currently samples approximately 3.54 million households each year, with a single address not being sampled more than once every 5 years (Herman, 2008; Capone *et al.*, 2020; U.S. Census Bureau, 2021c, 2022a). The data are currently available in 1-year and 5-year estimates; while the 5-year samples have the largest sample size and are considered the most reliable, they include data aggregated across the previous 5 years and are thus not as up-to-date as the most recent annual data (U.S. Census Bureau, 2022b). Annual data are reported for geographic entities with at least 65,000 people while supplemental one-year data is released for areas with 20,000 or more people and areas with fewer than 20,000 people are only available in 5-year estimates (Hertz Hattis, 2020). In 2021, there were 3,538,442 initial addresses selected and data were collected from 1,950,832 interviews (U.S. Census Bureau, 2021d). Each surveyed household is given a household weight that represents the quantity of households represented by that household's data and each individual within the household is also assigned person weight that reflects the population represented by that individual's data (Ruggles *et al.*, 2022). The ACS form that is distributed to individual households collects data on access to indoor plumbing and the cost of water and sewer (Table 3), but the form distributed to group quarters (e.g., nursing facilities, college/university student housing, correctional facilities, and barracks) does not include these questions (U.S. Census Bureau, 2023).

The ACS currently asks about indoor plumbing (Table 3), but the information is limited due to a 42% nonresponse rate for this question (based on 2017 5-year estimates) which is quite high when compared to a <3% nonresponse rate for other household plumbing questions (Capone *et al.*, 2020). In 2016, the ACS removed flush toilet as an answer choice, precluding tracking changes past 2015 (U.S. Census Bureau, 2015a, 2016). The 5-year estimates for 2011–2015 estimate that there are 782,084 residents in the U.S. (or 0.25% of the U.S. population) who do not have access to a flush toilet (Ruggles *et al.*, 2022). The states with the largest percentages of residents without flush toilets were Alaska (1.04%), New Mexico (0.69%), Arizona (0.42%), Maine (0.42%), and Alabama (0.41%) (Ruggles *et al.*, 2022). Although the ACS asks about the cost of water and sewer over the past 12 months (Table 3), it does not clarify if the services are affordable, reliable, and functioning properly

**Table 3** | 2023 ACS questions related to water and wastewater access (U.S. Census Bureau, 2023).

Does this house, apartment, or mobile home have–	Yes	No
a. hot and cold running water?	<input type="checkbox"/>	<input type="checkbox"/>
b. a bathtub or shower?	<input type="checkbox"/>	<input type="checkbox"/>
c. a sink with a faucet?	<input type="checkbox"/>	<input type="checkbox"/>
d. a stove or range?	<input type="checkbox"/>	<input type="checkbox"/>
e. a refrigerator?	<input type="checkbox"/>	<input type="checkbox"/>
<i>flush toilet? (removed in 2016)</i>	<input type="checkbox"/>	<input type="checkbox"/>
<b>In the past 12 months, what was the cost of water and sewer for this house, apartment, or mobile home? If you have lived here less than 12 months, estimate the cost.</b> Past 12 months' cost – Dollars	\$ X,XXX.00 <b>Or</b> <input type="checkbox"/> Included in rent or condominium fee <input type="checkbox"/> No charge	

(US Water Alliance and DigDeep, 2019). As of 2023, the ACS does not include questions about wastewater disposal method.

The U.S. Census Bureau considers anything not urban to be rural areas (Ratcliffe *et al.*, 2016). Urban areas are assessed at the census block level (smallest geographical unit for the U.S. Census Bureau surveys) based on total population thresholds and densities, land use, and development distance (Ratcliffe *et al.*, 2016). Urbanized areas have total populations of more than 50,000 people while urban clusters have between 2,500 and 50,000 people (Ratcliffe *et al.*, 2016). An urban area must have a population density of at least 1,000 people per square mile or 500 people per square mile if the block contains nonresidential land use (Ratcliffe *et al.*, 2016). Land use considers land cover and impervious surfaces that are within a quarter mile of an urban area (Ratcliffe *et al.*, 2016). For development distance, there is a hop criteria that determines if an area is within half a mile from urban development along a road corridor (Ratcliffe *et al.*, 2016). The U.S. Census Bureau delineates Core-Based Statistical Areas or Metropolitan and Micropolitan areas for statistical purposes with the remaining areas considered nonmetropolitan areas (Ratcliffe *et al.*, 2016). Nonmetropolitan areas are often considered synonymous with rural, but these geographical entities only have some overlap and are not identical (Ratcliffe *et al.*, 2016). Counties are listed as completely rural, mostly rural, or mostly urban with the classifications updated following each Decennial Census (Ratcliffe *et al.*, 2016). The annual ACS data will be updated the second year after the Decennial Census and will continue to use that classification for a decade (Ratcliffe *et al.*, 2016).

## AMERICAN HOUSING SURVEY

The AHS is the biennial survey that is sponsored by the U.S. Department of Housing and Urban Development (HUD) and administered in odd-numbered years by the U.S. Census Bureau (Figure 1; U.S. Census Bureau, 2020a; Table 4). This longitudinal survey aims to collect responses from the same households with new representative national samples being determined every 10 years or so (U.S. Census Bureau, 2019, 2020a, 2022c). Starting in 2015, there were about 115,000 households selected to participate until 2025 or until a new sample is drawn (U.S. Census Bureau, 2022d). This sample set includes a base sample of approximately 85,000 housing units for the national sample and additional housing units for an oversampling of select metropolitan areas and HUD-assisted housing units (U.S. Census Bureau, 2022d). The goal of each survey is to generate nationally representative data, but budget constraints typically only allow for samples from 30 metropolitan areas (U.S. Census Bureau, 2022d). The survey has four strategic goals and the first one is to ‘provide data to measure the quality, accessibility, and resiliency of the housing stock’ which includes the housing unit’s physical adequacy based partly on the unit’s plumbing and sewage disposal (U.S. Department of Housing and Urban Development *et al.*, 2020). The

**Table 4** | 2021 AHS sample sets (U.S. Census Bureau *et al.*, 2022a, 2022b).

Sample set for 2021	Total selected housing units	Housing units that were determined to be ineligible	Housing units that were surveyed	Housing units that completed survey	Overall response rate
Integrate National Sample	95,295	2,295	93,000	64,141	69%
Independent Metropolitan Area Samples	82,504	1,733	80,771	54,632	68%
<b>Total</b>	<b>177,799</b>	<b>4,028</b>	<b>173,771</b>	<b>118,773</b>	

AHS asks questions regarding both sewage disposal and indoor plumbing (Table 5 and Supplementary Table S1) in the ‘core’ data, but also has a series of ‘topical’ data questions that rotate each time the survey is administered (U.S. Census Bureau, 2022d) which could provide an opportunity for different questions to be introduced. The 2021 AHS asks questions regarding sewage disposal, indoor plumbing, toilet and sewage system breakdowns, water and sewer utility costs, and utility shut-offs (Table 5 and Supplementary Table S1).

While AHS data are useful, the AHS is less comprehensive with reporting data only from only certain states and select metropolitan areas, representing only 39% of urban populations in the U.S. (Capone *et al.*, 2020). It does not have an extensive sample of rural areas and does not sample group quarters like the ACS (US Water Alliance and DigDeep, 2019; U.S. Census Bureau, 2022d). The households are assigned to a rural/urban/suburban category when they first complete the survey without adjustments in subsequent years even though metropolitan areas may grow such that some suburban respondents become urban and some rural become suburban (NOWRA, 2017) before a new sample set is drawn; this results in a decreased proportion of rural respondents over time (NOWRA, 2017).

Although the U.S. currently does not have a survey that is collecting wastewater data as comprehensively as the Decennial U.S. Census, the AHS is the most recent national wastewater data set. It reported in 2021 that 108,574,000 housing units (84.5% of occupied housing units) are connected to public sewer and 19.5 million housing units used septic tank systems or cesspools (15.2% of occupied housing units) (Table 6), but experts in the onsite industry do not view these data as accurate (NOWRA, 2018; U.S. Census Bureau, 2021e; U.S. EPA, 2021c). The EPA does not consider cesspools to be adequate treatment systems since they are designed solely for waste disposal without any intention to treat the waste, but the AHS categorizes septic tank systems with

**Table 5** | 2021 select AHS questions on sewage disposal and indoor plumbing (U.S. Census Bureau, 2022e).

Question ID	Coded question	Answer choices
PUBSEWQ	Is ‘this building’ (housing type) connected to a public sewer?	1. Yes 2. No
SEWDISV	(Last time) we recorded that your (housing type) used ^ISEWDISTP septic tank or cesspool for sewage disposal. Is this information still correct?	1. Yes 2. No
SEWDISQ	What means of sewage disposal does ‘this building’ (housing type) have?	1. Septic tank 2. Cesspool 3. Chemical toilet 4. Outhouse or privy 5. Other; specify 6. None
SEWDISTP	What type of septic tank or cesspool system do you have? Read all answer categories. Refer to the help screen for more details on the types of septic tank or cesspool systems.	1. Standard septic tank and subsurface leach field (most common type) 2. Uses a pump to distribute wastewater 3. Elevated above natural soil surface 4. Applies treated wastewater 5. Any type not listed above
TOILET2	Does ‘this building’ (housing type) have a toilet?	1. Yes 2. No

*Note:* The questions are coded to autofill information. For ease of reading, ‘^your\_the\_that’ was replaced with ‘this building’ and ^HTYPEFILL was replaced with (housing type).



**Table 6** | 2021 National – plumbing, water, and sewage disposal – all occupied units (U.S. Census Bureau, 2021e).

Total (Households)	128,504,000
<i>Type of sewage system</i>	
Public sewer	108,574,000
Septic tank or cesspool	19,489,000
Standard septic tank and subsurface leach field	18,371,000
Pump used to distribute wastewater	633,000
Elevated above natural soil surface	291,000
Applied treated wastewater	66,000
Other	128,000
Other	185,000
None	123,000
Not reported	132,000

cesspools, making it difficult to use these data sets to determine if the households have an adequate decentralized treatment system (U.S. EPA, 2021c).

Many residents are unaware of their sewage disposal method (unless they are paying a monthly sewer bill) as may be the case with the 132,000 housing units with no reported sewage systems and the 185,000 housing units classified as ‘other’ (Table 6). The answer choice options for question coded SEWDISTP were (1) standard septic tank and subsurface leach field (most common type), (2) uses a pump to distribute wastewater, (3) elevated above natural soil surface, (4) applies treated wastewater, and (5) any type not listed above, but none of these would be common knowledge to the average U.S. resident unless they were involved in the design and installation of their OWTS. In addition, answer choice 1 being listed as the most common (Table 5) could potentially bias the interviewee’s response. Of the housing units reported to be on septic tanks or cesspools, there were 320,000 units that reported breakdown(s) in the last 3 months (Supplementary Table S3); the examples listed, which ‘could include tank collapse or explosion and tank being unable to perk resulting in a pump out’ indicate a deep lack of understanding of the functioning of septic systems by those who drafted the question (U.S. Census Bureau, 2021f). Breakdown data is not collected for houses that are classified as ‘other’, ‘none’, and ‘not reported’ (444,000 housing units) (U.S. Census Bureau, 2021f). In 2015, the AHS survey added ‘none’ as an option for wastewater system and 199,000 homes were categorized under this option (U.S. Census Bureau, 2015b). In 2021, the number of homes with ‘none’ sewage system had decreased to 123,000, while the number of represented housing units increased by 10.2 million (U.S. Census Bureau, 2015b, 2019). It is also interesting to note that the data for ‘none’ in 2017 did not meet publication standards and was withheld to avoid disclosure (U.S. Census Bureau, 2017). Although most of the data for incomplete bathrooms in 2021 also did not meet publication standards, the AHS did report that 136,000 housing units were without a complete bathroom (flush toilet, bathtub or shower, and a sink) and 116,000 housing units had no bathroom (U.S. Census Bureau, 2021f; Supplementary Table S2).

The AHS uses the responses from the survey to classify housing units as adequate, moderately inadequate, or severely inadequate; reasons including heating, electrical, upkeep, and also plumbing. Numerous plumbing conditions will result in a housing unit being classified as moderately inadequate, including at least three occurrences in the last 3 months of no functioning flush toilet for six or more hours, while some of the conditions for a housing

unit to be deemed severely inadequate are no hot or cold piped water, no full bathroom, or sharing a bathroom with members from another household (U.S. Census Bureau, 2021f). In 2021, there were 6.7 million housing units that were moderately or severely inadequate and over 2.5 million housing units that were without a functioning flush toilet at some point in the 3 months before the survey was collected (Supplementary Table S3). The AHS states that a flush toilet breakdown may be the result of ‘a faulty flushing mechanism, broken pipes, stopped up sewer pipes, lack of water supplied to the flush toilet, or some other reason’ including breakdowns due to natural disasters (U.S. Census Bureau, 2021f). It is shocking that a developed country would have roughly 6.6 million residents (based on an average household size of 2.60 persons (U.S. Census Bureau, 2022f)) without access to a flush toilet at some point during 2021.

## U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT POINT-IN-TIME (PIT) COUNT SURVEY

The U.S. Department of Housing and Urban Development conducts a Point-in-Time (PIT) count in January through its Continuum of Care (CoC) program in order to count people experiencing homelessness in both sheltered and unsheltered circumstances (U.S. Department of Housing and Urban Development, 2023). CoC is required to annually count the number of people on a single night in emergency shelters, transitional housing, and Safe Havens across the country which also includes domestic violence shelters and voucher-funded hotel and motel rooms (Meyer *et al.*, 2023; U.S. Department of Housing and Urban Development, 2023). Every other year, the CoC is also required to count the number of unsheltered people experiencing homelessness (U.S. Department of Housing and Urban Development, 2023). These counts are locally planned, coordinated, and conducted (U.S. Department of Housing and Urban Development, 2023). In 2022, the survey estimated 582,462 people were experiencing homelessness in U.S. states and territories with the majority (roughly 60%) residing in sheltered facilities (U.S. Department of Housing and Urban Development, 2023). Currently, this survey effort does not collect data on sanitation access for these populations, but it would be quite valuable to include questions regarding sanitation access since these populations are often not counted by other federal surveys unless they are receiving services at an address surveyed by the U.S. Census Bureau (U.S. Census Bureau, 2020a, 2020b, 2022c).

The 2020 Decennial Census was designed to count people receiving services at emergency and transitional shelters, soup kitchens, and regularly scheduled mobile food vans either with in-person interviews or based on facility records (U.S. Census Bureau, 2020b), but a study comparing data from PIT, ACS, 2010 Decennial Census, and Homeless Management Information System (HMIS) databases found that there were many sheltered residents experiencing homelessness who were classified as housed or in other group quarters for the surveys conducted by the U.S. Census Bureau primarily due to differences between the definition used to classify homeless shelters in the U.S. Census Bureau surveys and the PIT (Meyer *et al.*, 2023). This study found that 80–95% of residents in HMIS shelters were counted in the 2010 Decennial Census, but only 35–45% were included in the sheltered homeless count and the others were counted as in other types of group quarters, housed, or unsheltered (Meyer *et al.*, 2023). The study also revealed extensive double counting for 21–24% of sheltered populations experiencing homelessness, 45–56% of those recorded based on meal services, and 29–35% of unsheltered populations primarily due to residents being included in counts for shelters where they occasionally reside or were residing for part of the few months in which data is collected (Meyer *et al.*, 2023).

The PIT count and the U.S. Census Bureau depend on the expertise of local groups to identify unsheltered locations where people are residing (U.S. Census Bureau, 2020b; U.S. Department of Housing and Urban Development, 2023), but there are still many difficulties with fully estimating the ‘marginally housed’ or residents living in less public outdoor areas, in automobiles, or temporarily with friends and family especially since these

populations often fluctuate (Smith & Castañeda-Tinoco, 2019). There is also a limited count of residents experiencing homelessness in rural settings due to not all states having ‘Balance of State’ (BoS) or statewide CoC (Yousey & Samudra, 2018).

People experiencing homelessness must rely on shared sanitation facilities with limited upkeep (Frye *et al.*, 2019) (limited sanitation access) or open defecation (Capone *et al.*, 2018; Amato *et al.*, 2022) which needs to be included when collecting and evaluating wastewater data for all U.S. residents, but clearly they are not currently reported as part of the U.S. data to the JMP’s global monitoring of sanitation access data.

## OTHER EFFORTS TO COLLECT WASTEWATER DATA IN THE U.S.

OWTS permits (for new installation and repair/replacement) are maintained at county and/or state levels with inspections typically only occurring at installation, replacements, and real estate transactions. A study conducted by the National Environmental Services Center at West Virginia University compiled OWTS permits from 2015 through 2018 by reaching out to state regulatory agencies and local permitting agencies individually to collect this data (National Environmental Services Center, 2021). Phase 1 of the study focused on collecting data only from 2015 with an 82% response rate, while Phase 2 only had a 45% response rate when expanding the data to include 2016–2018 (National Environmental Services Center, 2021). While the study has limitations in its reliability for a nationwide analysis (National Environmental Services Center, 2021), it is currently the only one of its kind. This study found that the majority of OWTS permits (70%) were administered for new OWTS while 30% were administered for repair or replacements of existing OWTS (National Environmental Services Center, 2021). Using data on new installation permits and new housing development, the study developed an onsite system utilization rate (OSUR) that estimated 29–32% of new housing units use OWTS (compared to only 23% in 1993) (National Environmental Services Center, 2021) which indicates that there is an increase in OWTS installation throughout 2015–2018, but the AHS showed a decrease in houses utilizing OWTS between 2015 and 2019 (23.2 million to 20.3 million while the housing stock increased by nearly 6 million housing units) (U.S. Census Bureau, 2015b, 2019). Even with the study’s focus on OWTS permits and not OWTS usage, it provides valuable information on the changes to OWTS that is more recent than the 1990 Decennial Census and is more reliable than data collected from homeowners.

Other efforts to collect onsite wastewater data in the U.S. have focused on single states or on the usage of specific methods for wastewater disposal such as straight pipes or cesspools. Efforts to collect straight pipe (surface discharges of raw wastewater) data have documented their presence in 15 states using home-to-home inspections, agency reporting, resident self-reporting, expert estimate/opinions, and infrared aerial surveying (Maxcy-Brown *et al.*, 2021). The Minnesota Pollution Control Agency had the most comprehensive state-level data with estimates for straight pipe usage per county until a transition to reporting imminent threats to public health and safety together, but the agency is actively providing grants to replace failing OWTS (Helland, 2004; McCormick & Dowling, 2020; Maxcy-Brown *et al.*, 2021; Minnesota Pollution Control Agency, 2022). The Eastern Kentucky PRIDE program actively collected straight pipe data from 40 counties; their last large-scale survey in 2000 revealed that 6 counties had greater than 15% of homes using straight pipes (The Kentucky Water Resources Research Institute, 2001; Maxcy-Brown *et al.*, 2021). From 1997 to 2011, the North Carolina Department of Environmental and Natural Resources documented data on existing failing OWTS and system repairs in 23 counties (NC-DENR, 2010; Maxcy-Brown *et al.*, 2021). Efforts in Alabama have documented the use of straight pipes and unpermitted OWTS in three counties; including one county where up to 60% of sampled houses were using straight pipes and another county where 59% of sampled houses were without a permitted OWTS (White & Jones, 2006; Elliott *et al.*, 2017). Cesspools are being actively reported and eliminated in Hawaii (Mezzacapo *et al.*, 2020; State of Hawaii Department of Health, 2021; Coleman, 2022) and New York

(Smith & Myott, 1975; Hall, 2020; The Island Now, 2021), but have also been documented in Alabama (Flowers, 2020), Mississippi (US Water Alliance and DigDeep, 2019), and Oregon (Rush Locates, n.d.). There are currently no publicly available state-wide reports for failing outhouses and bucket latrines, but reports for smaller geographical areas have stated that outhouses are still used in Navajo Nations, Texas Colonias, and Amish communities (Pressley, 1999; McKenzie, 2002; Associated Press, 2015; US Water Alliance and DigDeep, 2019), and bucket latrines (commonly known as honeybuckets) are used in some of the over 3,300 rural homes in Alaska without piped water and flush toilets (Eddy, 2004; Chambers *et al.*, 2009; Eichelberger *et al.*, 2021; Mattos *et al.*, 2021a; Alaska Department of Environmental Conservation, 2022). Many of these data collection techniques have limited scopes because they require site-by-site surveys which can be costly due to their time- and labor-intensive nature.

## INTRODUCTION OF WASTEWATER QUESTION TO THE ACS

Through years of efforts by the National Onsite Wastewater Recycling Association (NOWRA) and a proposal submitted by the EPA, the U.S. Census Bureau has decided to test the inclusion of question H16 (Table 1) from the long-form Decennial Census in the annual ACS (NOWRA, 2018). The process formally began in 2018, but it is expected to take at least 5 years to fully test the inclusion before the question will be in the officially distributed ACS (NOWRA, 2018). It is anticipated to be included in the 2025 ACS Survey (U.S. EPA, 2021c). Therefore, a more accurate count of U.S. residents who are using septic tank systems should be available in the coming years, which should better inform policy decisions, manufacturing efforts, and research. Although the question has limitations, this is an important step toward collecting wastewater data that more accurately represents wastewater management in the U.S.

## CURRENT PERCENTAGE OF U.S. HOUSEHOLDS USING OWTS

As noted throughout this article, there is no recent and reliable estimate of the number of U.S. households with sewer connections vs. those with OWTS. The 2021 estimate from the Census Bureau (sourced from the AHS) of 15.2% occupied housing units; this estimate is universally regarded as erroneous by the OWTS community (NOWRA, 2018) and diverse lines of evidence demonstrate that it is implausible. The baseline percentage of households with OWTS during the 1990 Decennial Census was 24.12%, and this rate is very similar to that for new homes installed in 1993 and 1998 (23.2 and 24.3%) (National Environmental Services Center, 2021). Further, a substantial increase in the percentage of new housing units with OWTS has been documented for 2015–2018 (29.1–31.8%). This increase and the addition of roughly 36 million housing units since 1990 is inconsistent with the AHS estimate that in 2021 there were about 2.7 million fewer occupied housing units with OWTS than in 1990 and a 37.1% decrease in the percentage of housing units using OWTS (U.S. Census Bureau, 1993, 2021e, 2021g; National Environmental Services Center, 2021). The National Environmental Services Center also found that a previous U.S. Census Bureau study reported that roughly 3% of residential houses across a 4-year period were built without a permit (National Environmental Services Center, 2021) which would exclude homes with OWTS from construction estimations. In addition, the U.S. Census Survey of Construction does not include mobile (prefabricated) homes, the AHS is more likely to incorrectly mark rural homes as vacant, and some measurements count clusters of 6 or more homes connected to shared septic systems as connected to public sewer (NOWRA, 2017; U.S. EPA, 2021c). This shows that OWTS usage rates are being underestimated across multiple measures. In this section, we propose to generate the first defensible estimate of OWTS usage since the 1990 Decennial Census.

The estimated national usage of OWTS for 1990–2021 and a contrast with the published AHS data are included in Table 7 and Supplementary Table S4. It is based on data from the 1990 U.S. Decennial Census (U.S. Census

**Table 7** | Estimated OWTS usage for U.S. households.

Year	Total Number of Occupied Housing Units	Occupied Housing Units with OWTS	Percentage of Occupied Housing Units with OWTS	Average Percentage of New Housing Units with OWTS	Number of New Occupied Housing Units Since Previous Year of Data	Estimated Total Number of New Occupied Housing Units with OWTS	Estimated Occupied Housing Units with OWTS	Estimated Percentage of Occupied Housing Units with OWTS	Difference in OWTS Estimate and AHS Estimate
1990	91,947,410	22,182,101	24.12%	-	-	-	22,182,101	24.12%	-
1991	93,147,000	21,672,000	23.27%	23.76%	1,199,590	284,991	22,467,092	24.12%	795,092
1993	94,724,000	21,807,000	23.02%	23.25%	1,577,000	366,629	22,833,721	24.11%	1,026,721
1995	97,693,000	22,296,000	22.82%	23.76%	2,969,000	705,356	23,539,077	24.09%	1,243,077
1997	99,487,000	22,479,000	22.59%	23.76%	1,794,000	426,207	23,965,285	24.09%	1,486,285
1999	102,803,000	22,753,000	22.13%	24.45%	3,316,000	810,806	24,776,091	24.10%	2,023,091
2001	106,261,000	22,328,000	21.01%	25.15%	3,458,000	869,643	25,645,734	24.13%	3,317,734
2003	105,842,000	21,697,000	20.50%	25.83%	-419,000	-108,230	25,537,504	24.13%	3,840,504
2005	108,871,000	21,967,000	20.18%	26.51%	3,029,000	803,088	26,340,592	24.19%	4,373,592
2007	110,692,000	21,927,000	19.81%	27.20%	1,821,000	495,223	26,835,815	24.24%	4,908,815
2009	111,806,000	22,307,000	19.95%	27.88%	1,114,000	310,560	27,146,375	24.28%	4,839,375
2011	114,833,000	22,378,000	19.49%	28.56%	3,027,000	864,502	28,010,877	24.39%	5,632,877
2013	115,852,000	21,498,000	18.56%	29.24%	1,019,000	297,981	28,308,857	24.44%	6,810,857
2015	118,290,000	23,217,000	19.63%	29.94%	2,438,000	729,847	29,038,704	24.55%	5,821,704
2017	121,560,000	21,718,000	17.87%	31.35%	3,270,000	1,025,114	30,063,818	24.73%	8,345,818
2019	124,135,000	20,293,000	16.35%	29.78%	2,575,000	766,717	30,830,534	24.84%	10,537,534
2021	128,504,000	19,489,000	15.17%	30.47%	4,369,000	1,331,389	32,161,923	25.03%	12,672,923

Using the 1990 Decennial Census as the baseline (U.S. Census Bureau, 1993), with data from OWTS usage in new housing units (National Environmental Services Center, 2021) and estimates from the American Housing Survey (U.S. Census Bureau, 2021g), this table provides updated estimates of OWTS usage through 2021.

Bureau, 1993), the National Environmental Services Center estimate for percentage of new housing units to use OWTS in 1993, 1998, and 2015–2018 (National Environmental Services Center, 2021), and the AHS estimate of occupied housing units (U.S. Census Bureau, 2021g). The average of the given values for new housing units with OWTS in 1993 and 1998 was used to estimate new OWTS for 1991–1997. A simple linear regression was used to estimate the percentage of new housing units with OWTS for the years 1999–2014 based on the NESC point estimates for the percentage of new housing units with OWTS in 1998 and 2015. The estimate also used the average percentage of new housing units with OWTS between 2015 and 2018 to estimate new housing units with OWTS in 2019 and 2021 in order to compare with the most recent AHS data. The estimate calculations found that for 2021, it would be more accurate to estimate 32.2 million housing units use OWTS (25.03% of the U.S. housing stock), which is approximately 12.7 million more systems than the AHS 2021 estimate.

## DISCUSSION AND RECOMMENDATIONS

As publications continue to unveil the lack of equitable access to safely managed wastewater treatment (US Water Alliance and DigDeep, 2019; Capone *et al.*, 2020; Maxcy-Brown *et al.*, 2021) and the federal government develops programs to proactively address these wastewater issues (U.S. EPA, 2022a), there should be more systematic data collection nationwide to identify the housing units and people experiencing homelessness without access to safely managed sanitation and accurately track progress toward ensuring all wastewater is properly managed in the U.S. According to the EPA, ‘the existing data sources do not provide the information necessary to accurately characterize the use of decentralized systems nationally’ (U.S. EPA, 2021c), which is a major barrier to addressing wastewater inequities in the U.S.

The current data gaps are preventing policymakers and researchers from fully quantifying the costs and benefits of ensuring all residents have access to safely managed sanitation. The ACS determines how more than \$675 billion of federal spending are allocated each year (U.S. Census Bureau, 2022c), but it currently does not have mechanisms in place to account for the nationwide wastewater needs that require funding to address. As federally administered surveys continue to inform the distribution of federal funds, there should be a priority to fund these surveying efforts and to follow guidelines published by international agencies to collect sufficiently descriptive data (WHO & UNICEF, 2018; United States Agency for International Development *et al.*, 2021). Even with the introduction of the wastewater question from the Decennial Census to the ACS, there will be many data gaps in adequately capturing the wastewater issues currently experienced by residents throughout the country, especially those experiencing homelessness. Policies should be in place to prioritize the collection of wastewater data that reflect the current situation for all residents throughout the country without the exclusion of the residents relying on shared sanitation facilities, open defecation, OWTS, failing wastewater treatment systems, or no system.

Funding also needs to continue to be allocated to provide systems to the millions of affected Americans. The accessibility of funding should be improved so even homeowners and communities who currently lack the expertise will be able to apply. This is beginning to be possible through technical assistance funding in the Bipartisan Infrastructure Law (U.S. EPA, 2022a), but affected residents may need further assistance connecting with grant writers and engineers who have experience with small systems. All funding mechanisms are currently focused on the capital costs for installing the wastewater systems, but there also needs to be consideration for the long-term sustainability of systems that are installed. Many of the systems will serve low-income residents who are unable to afford the ongoing operation and maintenance expenses which could potentially prevent long-term access to safely managed sanitation. States should expand the administration of Clean Water State Revolving Funds (CWSRF) to decentralized projects (U.S. EPA Environmental Financial Advising Board, 2017) to ensure that all residents are able to access financial assistance for safely managed sanitation, not just ones connected to centralized sewer systems. In addition, funding should expand to provide resources and support for residents who are experiencing homelessness and improve their ability to access well-maintained public bathrooms and secure affordable, long-term housing solutions with safely managed sanitation (Frye *et al.*, 2019; Barker *et al.*, 2023).

The unique sanitation challenges faced by people experiencing homelessness require greater focus and resources, tailored to both sheltered and unsheltered contexts in urban and rural settings. Although the PIT provides the best available count of the extent of homelessness in the U.S., it has numerous challenges in generating data that are accurate, valid, and comparable across local CoC programs (Schneider *et al.*, 2018; Tsai & Alarcón, 2022). Currently, the PIT count methodology is highly variable across the U.S.; while this allows tailoring of sampling approaches and the survey instrument to the unique characteristics of each local context, it leads to inconsistencies in data quality and poor comparability across jurisdictions. The PIT could benefit from collaboration across regions to generate a standardized nationwide methodology, while acknowledging that approaches will need to be tailored to the specific setting (Schneider *et al.*, 2018; Tsai & Alarcón, 2022). The PIT currently relies on volunteers with limited training, so it is recommended that local and regional CoC programs share strategies for enabling more effective volunteer training and data collection (Schneider *et al.*, 2018; Smith & Castañeda-Tinoco, 2019; Tsai & Alarcón, 2022). Identified best practices include narrowing the responsibilities of volunteers to enable more specific and in-depth training, implementing advanced sampling methodologies, training volunteers to reduce sampling bias, collecting more descriptive data to inform the types of resources needed, spreading awareness of the counting efforts, providing incentives for participation, and expanding the network of organizations involved in the count (Schneider *et al.*, 2018; Tsai & Alarcón, 2022). Communities that have specific initiatives prior to the PIT count for advertising the count are able to establish more accurate

perceptions and improve the understanding of the PIT count for local residents, volunteers, and individuals experiencing homelessness (Schneider *et al.*, 2018). These marketing techniques have also resulted in increased volunteer support, financial resources, and support from influential community members (Schneider *et al.*, 2018). Community partnerships and support from local governments, community leaders, and private sector have the potential to improve the resources available for the PIT which can make it more effective (Schneider *et al.*, 2018). It is also recommended that data collection efforts focus more on identifying and counting marginally housed populations using strategies such as surveying anyone who may potentially be experiencing homelessness, implementing ‘respondent-driven sampling’, including day labor worker sites, taking special consideration for including immigrants and undocumented populations, and ensuring that similar resources are implemented to document rural homelessness as those resources used for urban homelessness (Yousey & Samudra, 2018; Smith & Castañeda-Tinoco, 2019; Tsai & Alarcón, 2022). Strategies to avoid double counting such as comparing respondent data between unsheltered and sheltered counts, comparing Census data with HMIS databases, collecting the last four digits of the respondent’s social security number, recording physical characteristics and location of the respondents, or collecting other unique identifiers (Smith & Castañeda-Tinoco, 2019; Meyer *et al.*, 2023). It has also been suggested that the PIT could potentially be replaced by other data sources such as epidemiological surveys or local ‘by-name lists’ that provide just-in-time information and leveraging technologies to account and track residents experiencing homelessness (Tsai & Alarcón, 2022). Having improved data on residents experiencing homelessness will not only improve understanding of the scope of their sanitation challenges, but will also enable organizations to have better data for their efforts to serve these residents and apply for financial assistance (Smith & Castañeda-Tinoco, 2019).

The current Administration has put forth many efforts to ensure that resources are made available to address environmental justice issues throughout the country and ensure that all residents have equitable access to healthy environments. These efforts for wastewater equity include the addition of specific language in legislation authorized funds specifically to disadvantaged communities (U.S. EPA, 2022a), the authorization of \$100 million for environmental justice grants (U.S. EPA, 2023a), the development of the EJScreen: Environmental Justice Screening and Mapping Tool (U.S. EPA, 2023b), the launching of Closing America’s Wastewater Access Gap Community Initiative (U.S. EPA, 2022b), Justice40 (Young *et al.*, 2021; The White House, 2022), and more. These efforts could be more efficiently expanded with accurate, comprehensive wastewater access data to target areas where solutions need to be mobilized.

To complement the efforts of the federal government, state and local governments should take specific actions to determine impacted communities and authorize resources (funding, personnel, supplies, etc.) to communities with historic, ongoing environmental justice issues to ensure that all residents are protected from wastewater access challenges. These policies should include financial assistance to utility customer assistance programs and to residents with unaffordable OWTS. Funding should also be allocated to programs that support low-cost installations of low-flow plumbing fixtures, protect against water shut-offs, increase accessibility to resources, and other programs that directly improve local wastewater issues.

It is essential to have accurate and comprehensive data on wastewater access to determine which residents are experiencing issues and what policies would be effective to address these issues for protecting the human right to safely manage wastewater treatment for all residents in the U.S.

## CONCLUSIONS

To accurately track progress toward equitable sanitation access for all, improvements to the mechanisms used to collect wastewater access data in the U.S. are needed. It is concerning to see an under-prioritization of data on a key human right that is not only essential for protecting human health but also the environment. The AHS has

been relying on a limited sample set that under-samples in rural areas and has yielded a gross underestimation in the usage of OWTS. Despite being the only current nationwide source of wastewater data, the AHS estimates contradict related data and have been viewed as insufficient by the OWTS industry and the EPA (NOWRA, 2018; National Environmental Services Center, 2021; U.S. EPA, 2021c).

The U.S. is making a key step toward collecting more accurate wastewater access data by introducing the question on sewage disposal from the Decennial Census to the ACS, but there will still be gaps in understanding and interpreting the affordability, reliability, and functionality of residents' wastewater management. Most nationwide surveys are overlooking the populations experiencing homelessness, which excludes almost 600,000 residents from national data sets. Policies should be implemented to ensure equitable and accurate representation of wastewater access for all residents. There should be requirements to implement the use of these data to inform funding allocations that protect the human right to affordable, reliable sanitation for every resident in the U.S.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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