



Short Communication

Seasonal contamination of well-water in flood-prone *colonias* and other unincorporated U.S. communities

Lewis Stetson Rowles III^a, Areeb I. Hossain^b, Isac Ramirez^a, Noah J. Durst^c, Peter M. Ward^d, Mary Jo Kirisits^a, Isabel Araiza^e, Desmond F. Lawler^a, Navid B. Saleh^{a,*}

^a Department of Civil, Architectural and Environmental Engineering, University of Texas, Austin, TX 78712, United States of America

^b Department of Biology, University of Texas, Austin, TX 78712, United States of America

^c School of Planning, Design and Construction, Michigan State University, East Lansing, MI 48824, United States of America

^d The Lyndon B. Johnson School of Public Affairs, University of Texas, Austin, TX 78712, United States of America

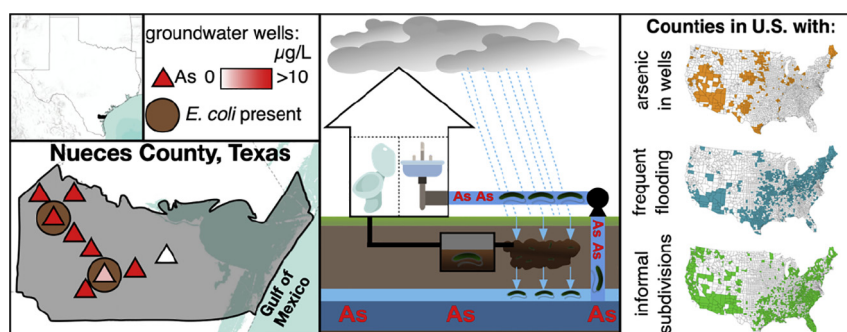
^e Department of Psychology and Sociology, Texas A&M University-Corpus Christi, Corpus Christi, TX 78412, United States of America

HIGHLIGHTS

- Unincorporated communities in the U.S. lack basic water infrastructure.
- Many *colonias* rely on water-wells and septic/cesspool systems not built to code.
- Well-water quality varies seasonally between arsenic and bacterial contamination.
- Seasonal contamination was dependent on the amount of rainfall.
- Nationwide analysis indicates similar water issues are likely throughout the U.S.

GRAPHICAL ABSTRACT

Well-water in Nueces County *colonias* cycles between arsenic and bacterial contamination and is dependent on the amount of rainfall, leaving such unincorporated communities vulnerable to health risks throughout the year.



ARTICLE INFO

Article history:

Received 19 April 2020

Received in revised form 4 June 2020

Accepted 8 June 2020

Available online 10 June 2020

Editor: Jay Gan

Keywords:

Peri-urban communities

Water quality

Arsenic

Microbial ecology

Groundwater wells

Low-income communities

ABSTRACT

Many of the six million residents of unincorporated communities in the United States depend on well-water to meet their needs. One group of unincorporated communities is the *colonias*, located primarily in several south-western U.S. states. Texas is home to the largest number of these self-built communities, of mostly low-income families, lacking basic infrastructure. While some states have regulations that mandate minimum infrastructure for these communities, water and sewage systems are still lacking for many of their residents. Unprotected wells and self-built septic/cesspool systems serve as the primary infrastructure for many such *colonias*. This research was designed to probe how wells and septic/cesspool systems are influenced by heavy rainfall events. Such events are hypothesized to impact water quality with regard to human health. Inorganic and microbiological water quality of the wells in nine *colonias* located in Nueces County, Texas, were evaluated during dry and wet periods. Nueces County was selected as an example based on its flooding history and the fact that many *colonias* there depend entirely on well-water and septic/cesspool systems. The results demonstrate that well-water quality in these communities varies seasonally with respect to arsenic (up to 35 µg/L) and bacterial contamination (*Escherichia coli*), dependent on the amount of rainfall, which leaves this population vulnerable to health risks during both wet and dry periods. Microbial community analyses were also conducted on selected samples. To explore similar seasonal contamination of well-water, an analysis of unincorporated communities, flooding

* Corresponding author.

E-mail address: navid.saleh@utexas.edu (N.B. Saleh).

frequency, and arsenic contamination in wells was conducted by county throughout the United States. This nationwide analysis indicates that unincorporated communities elsewhere in the United States are likely experiencing comparable challenges for potable water access because of a confluence of socioeconomic, infrastructural, and policy realities.

© 2020 Published by Elsevier B.V.

1. Introduction

Millions of Americans live in unincorporated peri-urban communities (i.e., communities that are located outside the city limits but are in commuting proximity) (Durst and Sullivan, 2019). The *colonias* are unincorporated communities along the United States-Mexico border in Texas and elsewhere in several other U.S. states. According to the Housing Assistance Council, there are >1800 *colonias* in Texas, 142 in New Mexico, 86 in Arizona, and 15 in California (Housing Assistance Council, 2012). Many such unincorporated peri-urban communities and their demographics and relative environmental poverty have remained largely unidentified or “invisible” across the nation (Ward, 2014; Ward and Peters, 2007). In these communities, land is acquired informally, and dwellings are either self-built or are manufactured homes, often with self-built additions. Compared with typical suburbs, these communities have minimal levels of physical infrastructure, e.g., unpaved roads, no piped water or sewage, and inadequate drainage and lighting, which lead to poor environmental conditions and environmental poverty (Durst et al., 2014). The *colonias* were originally developed as low-density neighborhoods with no infrastructure but have become more densely populated with some basic infrastructure built out of necessity (not to code) (Durst et al., 2014). When the socioeconomic conditions of these communities are overlaid on these factors, lack of access to resources becomes even more severe. Most of the 5.5 million *colonias* residents in the U.S. are low-income families (Housing Assistance Council, 2012). These compounding factors have reduced residents' access to potable water. Untreated, off-the-grid water from household and community wells is the only resource available to many of these residents, but evaluation of water quality in these communities is nearly non-existent.

Though the ‘Safe Drinking Water Act’ in the United States has improved water quality for many Americans since 1974, these regulations do not safeguard water systems that serve 25 people or less (United States Environmental Protection Agency, 2004). *Colonias* residents often construct wells to meet their water supply needs but pay little or no attention to drinking water standards. Thus, most of these wells are shallow and unprotected (Pritchard et al., 2008), which has led to waterborne disease outbreaks (e.g., cholera outbreaks in several *colonias* in the 1990s) (Knab, 2016). Substandard “septic” systems in the *colonias* have been correlated with gastrointestinal illnesses, respiratory problems, and skin infections (Rios and Meyer, 2009). Additionally, chemicals of concern can occur in groundwater in the *colonias*. The states that are home to the *colonias* (i.e., Texas, New Mexico, Arizona, and California) have hotspots of naturally occurring arsenic in the groundwater (Ryker, 2001). For instance, Texas, the state with the highest number of *colonias*, has groundwater in some areas (i.e., western Texas near El Paso and the Gulf of Mexico coast) that is known to contain arsenic as well as other potentially toxic compounds (e.g., nitrate, boron, vanadium) (Glenn and Lester, 2010; Hargrove et al., 2015). While little has been done to study or mitigate arsenic contamination in the *colonias*, the occurrence of microbial waterborne diseases prompted government restrictions on such settlements (Knab, 2016; U.S. Department of Health and Human Services, 2000). Forced improvements to housing infrastructure have made an apparent enhancement in the living conditions (Durst et al., 2014; Durst and Ward, 2016; Latin American Housing Network, 2009), but these efforts have been insufficient to provide potable water and improved sanitation.

Microbial waterborne diseases in unincorporated communities can be exacerbated by flooding events that have the potential to transport fecal pathogens from poorly built septic systems to the groundwater supply (Cooper et al., 2016; Fong et al., 2007; Gowrisankar et al., 2017). One area, with a number of *colonias*, that is prone to severe flooding due to its close proximity to the Gulf of Mexico, is Nueces County, Texas. Many *colonias* in this region lack piped water supply, so household wells are commonly utilized as the primary water source. Nueces County can be considered as an example for a large number of unincorporated communities throughout the U.S. that are likely to experience seasonal variation in water quality due to heavy rainfall events and poor water and sanitation infrastructure. While groundwater contamination in unincorporated communities has the potential to vary between metals (dry periods) and fecal pathogens (wet periods), no study to date has carefully explored this issue.

The influence of extreme weather events on water quality is well-known (Martinez et al., 2014; Park et al., 2010). In western Spain, for example, arsenic levels in wells increased during a drought due to reduced groundwater flows (García-Prieto et al., 2012). Similar results were reported in Australia, where a decrease in the water table caused an extreme arsenic spike (up to 7000 µg/L) (Appleyard et al., 2006). In West Africa, where seasonal variation in rainfall is common, fluoride concentration in groundwater (determined from boreholes) has been reported to be inversely correlated to monthly rainfall over an eight-month period (Alfredo et al., 2014). On the other hand, several studies have found that long-term flooding (e.g., monsoon season in Southeast Asia) can mobilize arsenic from the topsoil (Burton et al., 2014), whereas non-flooded soils can accumulate arsenic (Roberts et al., 2009; Takahashi et al., 2004). Overall, arsenic mobilization from soil or bedrock can be initiated by anoxic or anaerobic conditions, which lead to reductive dissolution (Burton et al., 2008; Stroud et al., 2011; Weber et al., 2010) or microbial reduction (Burton et al., 2014). Hydrogeological conditions also have been observed to influence the levels of arsenic and *E. coli* in groundwater wells in Bangladesh (Leber et al., 2011); wells with more permeable soils have exhibited lower arsenic concentrations but a higher concentration of *E. coli* in wet seasons as compared to wells with less permeable soils (Leber et al., 2011). These reports highlight the importance of contaminants varying in groundwater, particularly in areas where hydrogeologic conditions can change drastically over a short period of time. The heavy rainfall events commonly experienced in Nueces County, Texas, combined with the lack of infrastructure in the informal *colonias*, make the groundwater wells susceptible to contamination throughout the year.

This study is one of the first to systematically investigate seasonal variation of groundwater quality from wells in unincorporated communities in the U.S., and our main objective is to probe the potential for contaminant variation as a function of rainfall in this low-lying, coastal, and flood-prone area. The *colonias* in Texas are representative of similar unincorporated communities across the U.S., which are likely susceptible to a similar confluence of factors. A comprehensive assessment of the chemical and biological water quality (i.e., metal concentrations and microbial community structure) is completed during wet and dry periods. Because the *colonias* are comparable to informal housing elsewhere in Texas and beyond, the findings of this study will shed light on water quality challenges for a much larger low-income population in the U.S. To that end, an analysis of the confluence of factors, i.e., arsenic contamination of groundwater, flooding, and mobile home

distribution (as a surrogate of low-income, unincorporated communities), across the U.S. is presented, which identifies areas that might experience similar water quality issues.

2. Material and methods

2.1. Study area selection criteria and water sampling details

The area selected for this study, Nueces County, Texas (Fig. S1), is near the coast and has a long flooding history. A database from The Attorney General of Texas lists Nueces County as having 26 *colonias* but a non-profit, South Texas Colonia Initiative (STCI, 2018), estimates the number to be >150 (The Attorney General of Texas, n.d.). This discrepancy could be due to the fact that the state only tracks *colonias* that were developed in the pre-1990 era. Hundreds of new subdivisions, most of which rely on septic/cesspool systems, have been developed since the early 1990s (Durst and Ward, 2016). Nearly two-thirds of the residents in Nueces County *colonias* are living below the poverty line (yearly income < \$18,840/household), according to a 2009 study (Rios and Meyer, 2009). Many of the *colonias* use community or household wells, although some have access to a treated and piped water supply (Fig. S1). Water samples were collected from nine *colonias* in Nueces County; these *colonias* were chosen based on socioeconomic status and prior knowledge of arsenic contamination (guided by STCI). The *colonias* in this county lack a central sanitary sewer and rely on septic/cesspool systems for handling of domestic wastewater. A cesspool is an underground pit that is constructed of stone, brick, or concrete and it usually drains directly onto the surrounding soil. These cesspool systems, which do not meet the waste management standards, lack the ability to physically and biologically treat waste, unlike septic systems. Many of the domestic waste handling processes in the *colonias* are legacy systems, i.e., these are built by previous occupants of the dwelling; thus the exact type and construction standards followed are largely unknown by the current occupants.

Samples were collected directly at the well-head where possible (details included in Table S1). Water samples were collected from 14 individual household wells, two households on the same community well (Cyndie Park), one household with treated piped water, and one household that collects treated piped water and stores it in 50-gallon drums. Except for the Cyndie Park community well, which is quite deep, all others well that were samples were self-built and therefore shallow. The sampling events were chosen to capture the impact of a heavy rain-fall event and a dry spell: June 2018 after a major rain event (i.e., >38 cm over three days) and March 2019 during a dry period (i.e., <5 cm over eight weeks prior to sampling) (NOAA, 2019). One sample was collected from each location during both the wet and dry periods. During each sampling campaign, separate bottles were used for a range of water quality analyses. For growth-based microbial analyses, one 250-mL sample was collected in a polypropylene container at all sampling locations. At selected sampling locations, 2-L water samples were collected in sterile polypropylene containers for microbial community analyses. At each sampling location, part of a 50-mL sample was used for on-site measurements, and the remainder was stored on ice until analysis at UT Austin within 48 h.

2.2. Water quality analyses

On-site measurements included conductivity, pH, and temperature (Myron L Ultrameter III; Carlsbad, CA). Arsenic was measured with Quick Arsenic II test kits, a United States Environmental Protection Agency (US EPA) verified method (Industrial Test Systems Inc.; Rock Hill, SC). A comprehensive metals analysis (i.e., aluminum, barium, calcium, cadmium, chromium, cobalt, copper, iron, potassium, magnesium, sodium, nickel, lead, selenium, strontium, and zinc) was conducted with an Agilent 710-ES Inductively Coupled Plasma Optical Emission Spectrometer (Agilent Technologies; Santa Clara, CA). For preservation,

samples were acidified to 5% (v/v) with trace metal grade nitric acid, and National Institute of Standards and Technology (NIST)-certified standards were used for analyses. Heterotrophic plate counts (HPC) and total coliforms/*Escherichia coli* were measured with HPC and Colilert, respectively, in Quanti-2000 Trays (IDEXX; Westbrook, ME) per the manufacturer's instructions. These bacterial enumeration methods are US EPA approved and yield most probable number (MPN) for the bacteria of interest. Statistical analysis of the water quality data in wet and dry periods was conducted in R. Initially, a multivariate analysis of variance was utilized to test for a significant difference in contaminants between the periods. Then pairwise *t*-tests ($\alpha = 0.05$) were used to test for significant differences in specific contaminants between the periods.

2.3. DNA extraction and microbial community analysis

DNA was extracted with a DNeasy PowerWater Kit (Qiagen; Germantown, MD). Details of the sequencing and processing are provided in the SI (Section S1) and follow the procedure as previously described (Rowles III et al., 2019). In brief, DNA sequencing was completed by MR DNA (Molecular Research LP; Shallowater, TX) where the 16S rRNA gene V4 variable region was amplified with PCR primers 515F (GTGYCAGCMGCCGCGGTAA) and 926R (CCGYCAATYMTTTRAGTTT), with barcode on the forward primer. Generated operational taxonomic units (OTUs) were defined by clustering at 97% similarity. OTUs were classified using Basic Local Alignment Search Tool Nucleotide against a curated database derived from the National Center for Biotechnology Information (NCBI, 2019) and Ribosomal Database Project (RDP, 2016). The OTU and taxonomy tables were imported into R (SI Section S2) and combined into a phylogenetic tree with Phyloseq (McMurdie and Holmes, 2013) and Ape (Didier et al., 2019). The package GUniFrac (Chen, 2018) was then used to calculate Generalized UniFrac distances (Lozupone and Knight, 2005), which were used to conduct a principal coordinate analysis (PCoA) with Vegan (Oksanen et al., 2019).

2.4. Nationwide assessment of unincorporated communities with arsenic and flooding

To assess the location of unincorporated communities that could be experiencing similar shifts in water quality, a nationwide analysis of counties with arsenic, flooding, and mobile homes was completed. For the location of wells with naturally occurring arsenic, a study from the U.S. Geological Survey was utilized. In this study, arsenic concentration in 31,000 samples from several state and national databases was utilized to show counties with arsenic >5 µg/L in at least 25% of the wells (Ryker, 2001). For frequency of flooding, data from Federal Emergency Management Agency was utilized, i.e., counties with >20 floods from 1996 to 2013 (FEMA, 2015). When exploring the location of unincorporated communities, mobile homes can be a good surrogate measure because these communities usually consist of 10–50% mobile homes so counties with >2500 mobile homes were analyzed (Durst, 2019). Counties with all three of these factors (e.g., arsenic, flooding, and mobile homes) denote areas that could be experiencing similar shifts in water quality like those in the *colonias* of Nueces County.

3. Results and discussion

3.1. Elevated arsenic levels in well waters during dry period

Arsenic concentrations were >1 µg/L in all sampled wells, with the exception of Poenish Acres, during both sampling periods (Fig. 1a). The treated piped water sampled from two households did not contain any measurable arsenic. During the wet period, one sample from Primavera and both samples from Tierra Grande contained arsenic at the US EPA maximum contaminant level (MCL, 10 µg/L). During the dry period, 14 samples from all of the *colonias* except Petronila Estates and Poenish

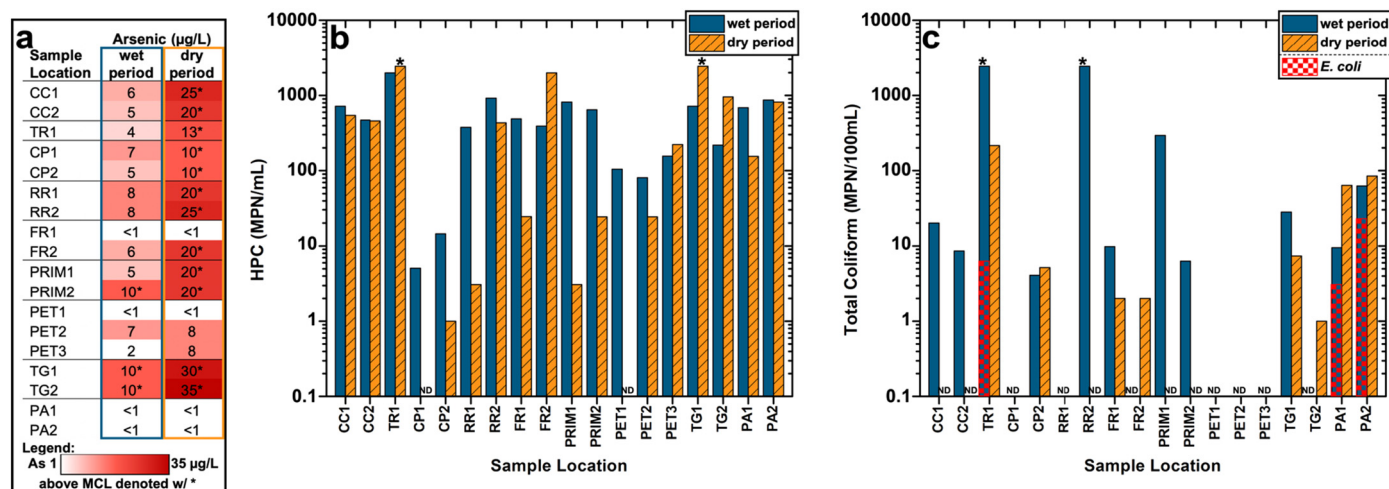


Fig. 1. Results from wet and dry periods of (a) arsenic concentration with color-coded scale established with respect to the US EPA primary maximum contaminant level (MCL) for drinking water, (b) heterotrophic plate count (HPC) and (c) total coliforms with *E. coli* concentration noted by red-checked pattern in most probable number (MPN). Samples with microbial counts below the detection limit, i.e., non-detect, are listed as ND, and samples too numerous to count are denoted with an asterisk (*). Colonias are Country Club (CC), The Ranch (TR), Cyndie Park (CP), Railroad (RR), Fiesta Ranch (FR), Primavera (PRIM), Petronia Estates (PET), Tierra Grande (TG), and Poenish Acres (PA). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Acres contained arsenic at alarming levels, well over the MCL (as high as 35 µg/L), which presents a direct health risk to the residents. It is notable that Cyndie Park's community well is regulated by the US EPA and is a serious violator for continued exceedance of the arsenic MCL along with failure to monitor/report other pollutants (US EPA, n.d.). The variation in arsenic concentration based on rainfall was apparent; i.e., during the dry period, arsenic concentrations were much higher at each site than their counterpart concentration during the wet period (p -value < 0.001). The underlying cause of such concentration variation is intriguing. A positive correlation between concentration of aqueous iron and arsenic, due to arsenic's interaction with iron hydroxides (Appleyard et al., 2006), was explored; a statistically significant difference was not observed between wet and dry periods for a co-presence of aqueous iron and arsenic. These results suggest that an alternative mechanism is likely responsible for elevated arsenic levels during the dry period. Future sampling efforts should measure the oxidation/reduction potential to investigate anoxic/anaerobic conditions (Stroud et al., 2011) and reductive dissolution (Burton et al., 2008; Weber et al., 2010). All other measured metal concentrations are shown in Tables S2 and S3.

The underlying causes of arsenic concentration variation seem to be related to the amount of rainfall. The elevated arsenic concentration in the dry period is likely due to loss of porewater from the natural drying process during an extended period without rain. Intentional withdrawal of water, in some cases over-withdrawal, has known to have caused similar concentration increase due to water table subsidence as reported by Smith et al. for a number of California groundwater wells (Smith et al., 2018). Similarly, Muehe et al. reported that an increase in seasonal temperature (claimed to have been caused by climate change) increased soil arsenic concentration in controlled experimental settings (Muehe et al., 2019). On the other hand, decreased arsenic levels during the wet period could be due to dilution from major rain events. Seasonal variation has been shown to modulate arsenic concentration where the amount of rainfall and hydrogeology can be key factors. In New England, elevated arsenic levels have been reported during dry months likely due to lowering of the water table (Ayotte et al., 2015). Conversely, groundwater recharge events (similar to those experienced in the sample area during the wet period) have shown to decrease arsenic concentration due to dilution by oxygenated water (Ayotte et al., 2015; Bondu et al., 2016). A three-year study of 20 wells in Bangladesh found that the concentration of arsenic in shallow wells (<10 m) varied greatly due to seasonal precipitation (Cheng

et al., 2005). Regional hydrogeology also can influence the arsenic concentration in wells. In Mexico, the concentration of arsenic in an unconfined aquifer of fractured limestone (where rainfall can quickly infiltrate) was found to be inversely related to the amount of monthly rainfall, in contrast to confined aquifers where arsenic concentrations were constant (Rodríguez et al., 2004). In Nueces County, the sampled wells are contained within the Holocene epoch, and the geology is mostly composed of alluvium, a loose unconfined soil, which can be substantially affected by rainfall (Glenn and Lester, 2010). The (lack of) depth in the wells and their soil composition in the Nueces County colonias seem to be responsible for the dilution of arsenic after major rainfall.

3.2. Seasonal microbial contamination of wells

The microbial results on the collected samples are also shown in Fig. 1. The relationship between HPCs and sampling time (i.e., wet or dry period) is not statistically significant with a p -value > 0.05 (Fig. 1b). However, the total coliform concentrations detected during the wet period were significantly greater (p -value 0.012) than those during the dry period (Fig. 1c). During the wet period, wells in The Ranch and Poenish Acres contained *E. coli*, which is a fecal indicator bacterium; this finding suggests possible contamination of these household wells from septic/cesspool systems during the heavy rainfall event (Arnade, 1999; Raina et al., 1999). Interestingly, the samples collected from the deeper Cyndie Park well showed no significant seasonal variation and contained lower HPCs and total coliform counts compared to the household (shallower) wells.

The impact of heavy rain on shallow groundwater wells is well documented. Heavy rainfall caused an increase in *E. coli* (Van Geen et al., 2011) and total coliform (Bennett et al., 2010) levels in shallow wells in Bangladesh and Cambodia, respectively. The US EPA requires at least 50 ft. (15.2 m) spacing between the septic system and groundwater wells, and Texas law requires a lot size of 20,000 ft² (1858 m²) for new septic systems to be installed (Texas Administrative Code, 1976). These requirements are to protect water sources because contamination of wells with coliforms can occur if septic tanks are positioned too close to the wells (Hynds et al., 2012; Pang et al., 2004; Won et al., 2013). However, nearly all of colonias lots are smaller than required, since they have been illegally subdivided, and the septic/cesspool systems in these lots have not been constructed to code. Additionally, fecal contamination of wells has also been found to increase significantly during

the wet period from on-site sanitation or poor construction (e.g., shallow or uncovered) (Kostyla et al., 2015; Msilimba and Wanda, 2013; Pritchard et al., 2007). The seasonal contamination of the shallow household wells in the *colonias* with coliforms and, in some cases, *E. coli* likely has been caused by flooding of the septic/cess-pool systems.

3.3. Microbial ecology reveals location specific impacts of flooding

Analysis of the bacterial communities in the sampled wells reveals distinct differences between the wet and dry periods for all locations except Cyndie Park. PCoA shows distinct clustering between the wet and dry periods in Cyndie Park with the two points nearly identical (Fig. S2). Further analyses with UniFrac distances (Table S4) can be used to assess pair-wise differences in microbial community composition ('0' means samples are identical and '1' means the samples do not share any branches in the phylogenetic tree). Comparing wet and dry periods by sample location and in order of increasing dissimilarity, the UniFrac distances were Cyndie Park 0.093, Tierra Grande 0.286, Country Club 0.399, and Poenish Acres 0.501. These results suggest that the microbial community of Cyndie Park is the least impacted from rain events, while Poenish Acres is most impacted. Interestingly, the diversity within each sample, i.e., alpha diversity (Table S5), is less in the wet period for Poenish Acres and Country Club as compared to that in the dry period. The reduction in diversity could be due to the dominance of the floodwater microbial community in the wells.

At the phylum level (Fig. 2), the bacterial community is dominated by Proteobacteria for both wet and dry periods with a relative abundance of 49%–95%. Proteobacteria, which includes beneficial and pathogenic Gram-negative bacteria (Garrrity et al., 2002), are common in groundwater (Kim et al., 2015). When comparing the microbial community between wet and dry periods at a single location, significant shifts in the predominant phyla were observed at all locations except for Cyndie Park, which has a deeper well than the other sites. Further exploring contamination associated with sewage (i.e., on-site septic/cesspool systems), several distinct microorganisms were present during the wet period. At Poenish Acres, Firmicutes was the second most dominant phylum. This phylum includes the genus *Carboxydotherrmus* (an endospore-forming and thermophilic group) (Whitman, 2009), which accounts for 25.8% of the total relative abundance during the wet period. Endospore-forming bacteria have been found to increase in number in soil after flooding (Casteel et al., 2006). At Country Club, the phylum Chloroflexi corresponding to the genus *Ornatilinea* (an obligate anaerobic mesophile found in wastewater) was present in the wet sample period (Bian et al., 2018; Podosokorskaya et al., 2013), and the phylum Planctomycetes corresponding to the genus *Candidatus Kuenenia* (an anammox bacterium found in septic tanks) was present during the

dry period (Jin et al., 2018). The presence of these organisms in Poenish Acres and Country Club suggest that septic/cesspool systems likely influenced the groundwater quality in these unincorporated communities; a correlation between septic systems and elevated microbial concentrations in groundwater during floods has been reported previously (Gowrisankar et al., 2017). Also, septic tanks have been found to release fecal coliforms, causing shifts in the surrounding microbial communities after major rain events (Cooper et al., 2016). In Ohio, massive microbial groundwater contamination was released from septic tanks due to a rise in the water table (Fong et al., 2007). In future studies, domestic waste as a source of the contamination in the groundwater could be probed by assessing the presence compounds that originate from the household, e.g., caffeine or laundry brighteners. Presence of these compounds in water gives direct evidence of contamination from domestic waste, as caffeine and brighteners are used in nearly all households. (Allevi et al., 2013; Meays et al., 2004)

3.4. Nationwide analysis of arsenic and flooding in unincorporated areas

The implications of seasonal water contamination are not limited to the example communities studied herein, i.e., those located in Nueces County. Fig. 3 shows a nationwide analysis of counties with arsenic, flooding, and mobile homes and provides a national insight into communities that possibly face similar issues to those found in the Nueces County *colonias*. Similar analyses could be performed for other natural inorganic contaminants, but arsenic was chosen because of its chronic toxicity and widespread occurrence. Naturally occurring arsenic can be found in wells throughout the U.S. with the exception of the southeast (Fig. 3a) (Ryker, 2001). Data from 1996 to 2013 reveals that flooding was more frequent in southern, northeastern, and central U.S. (Fig. 3b) (FEMA, 2015). Counties with >2500 mobile homes can be found throughout the country with the exception of the Midwest (Fig. 3c); the high number of mobile residences in these counties is interpreted to mean that these counties likely contain informal subdivisions similar to *colonias* or mobile home parks (Durst, 2019), both of which often lack adequate and affordable potable water (Chen et al., 2010; Pierce and Gonzalez, 2017). More broadly, however, informal subdivisions and mobile home parks exist in large numbers across unincorporated parts of the country and these suffer from distinct challenges, including high rates of poverty, exposure to concentrated unwanted land uses (e.g., landfills, industrial plants), and limited or poor-quality infrastructure and service provision (Anderson, 2008; Durst, 2019; MacTavish, 2007). Both types of communities are particularly vulnerable to storm damage due to poor-quality housing and infrastructure conditions (Collins, 2009; Fothergill and Peek, 2004; Kusenbach et al., 2010). Residents in these communities also experience greater tenure insecurity than those in formal neighborhoods (Olmedo and Ward, 2016; Sullivan, 2018). As illustrated in Fig. 3, the confluence of all the three factors (i.e., arsenic, flooding, and mobile homes) provides insight on possible locations of communities that might face similar issues to those found in the *colonias* of Nueces County.

Hotspots are identified with the overlapping factors of arsenic concentration, flooding, and mobile home density; the highest density of such areas has been found in Texas, New Mexico, Arizona, California, Nevada, and Maine (Fig. 3d). Interestingly, the border region with Mexico (i.e., Texas, New Mexico, Arizona, and California) is home to many *colonias* (Housing Assistance Council, 2012). Although states with *colonias* are shown to have the highest concentration of these hotspots, the counties identified in Maine and several others in the Midwest and Northeast also unexpectedly show an overlap in the probed factors. Given the similarities in financial conditions, types of dwellings, and life-style in other unincorporated communities or informal home-stead subdivisions in these identified counties, these areas will likely face water contamination issues similar to those found in the *colonias* in Nueces County, Texas.

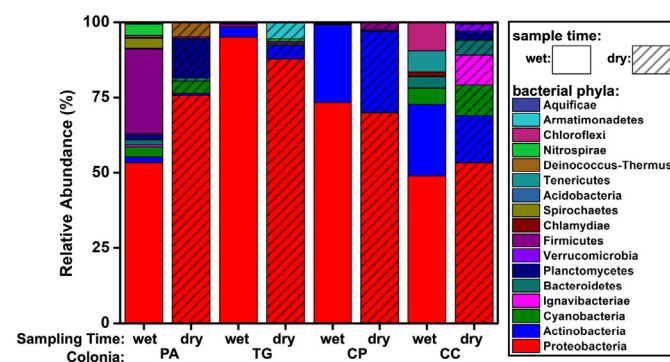


Fig. 2. Relative abundance of bacterial phyla from select locations during dry and wet periods. Colonias are Poenish Acres (PA), Tierra Grande (TG), Cyndie Park (CP), and Country Club (CC). Only operational taxonomic units comprising 0.5% or greater are shown.

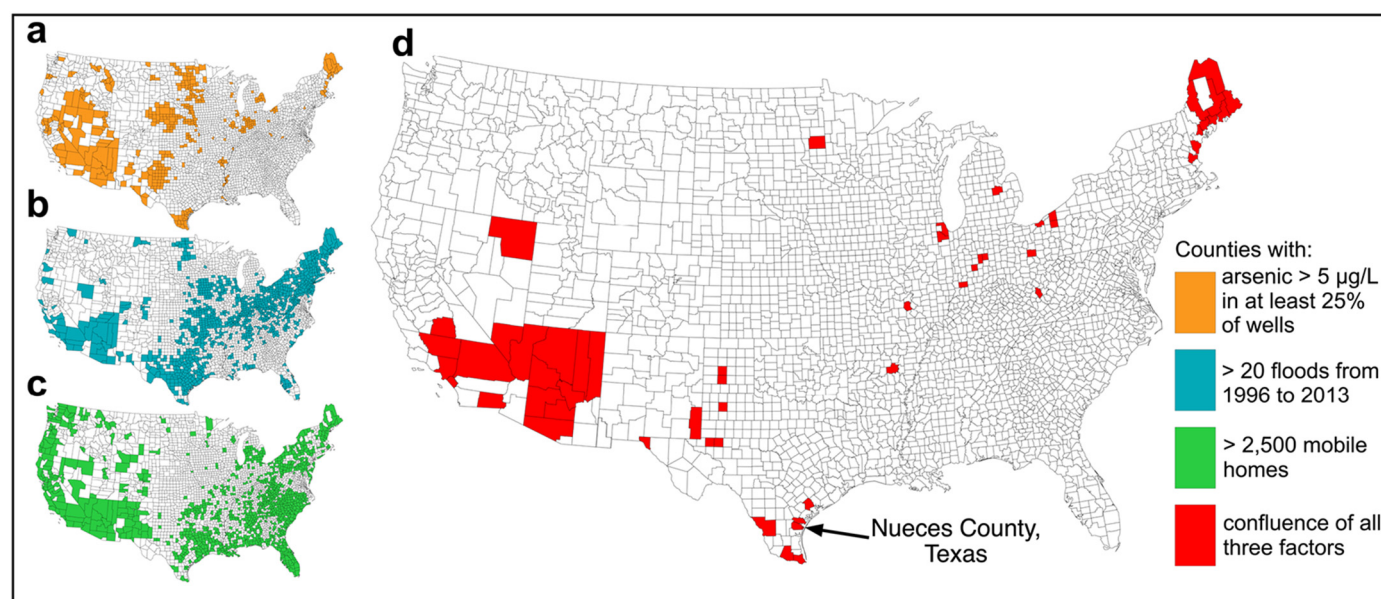


Fig. 3. Maps of the contiguous United States by county with (a) arsenic > 5 µg/L in at least 25% of wells, (b) > 20 floods from 1996 to 2013, (c) > 2500 mobile homes, and (d) confluence of all three factors.

4. Conclusions

This research is one of the first reports on seasonal variations (i.e., during floods vs. dry season) of water quality in *colonias*-type unincorporated communities. These communities exhibit conditions similar to developing countries and have been overlooked by many. As per the United Nations Sustainable Development Goal 6 (i.e., clean water and sanitation for all), these marginalized communities in the developed countries should not be ignored. The water quality assessed in the *colonias* located at Nueces County, Texas, reveals that these communities are exposed to arsenic and microbial contamination throughout the year with seasonal variation. As one of the first reports of water contamination in the *colonias*, these findings bring the spotlight to the estimated 400,000 *colonias* residents in Texas. However, they are not just a singular case located in Texas. Nearly six million people reside in such unincorporated communities across the United States. A nationwide analysis of reported arsenic concentration, flooding frequency, and density of mobile homes (which are the most common type of unincorporated housing) identifies regions where confluence of these factors is likely. This analysis indicates that communities in a number of states are vulnerable to water contamination challenges. Unincorporated communities or informal homestead subdivisions in the identified counties likely face similar socioeconomic and infrastructural issues. When hydrogeological factors combine with the lack of proper infrastructure, groundwater contamination issues that vary as a function of rain events become plausible. Thus, the results presented herein are not a local phenomenon, but rather a nationwide disparity in access to safe water in informal communities.

Credit authorship contribution statement

Lewis Stetson Rowles: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Areeb I. Hossain:** Investigation. **Isac Ramirez:** Investigation. **Noah J. Durst:** Formal analysis, Writing - review & editing. **Peter M. Ward:** Formal analysis, Writing - review & editing. **Mary Jo Kirisits:** Conceptualization, Supervision, Data curation, Writing - review & editing. **Isabel Araiza:** Investigation, Writing - original draft, Writing - review & editing. **Desmond F. Lawler:** Conceptualization, Supervision, Data curation, Writing - review & editing. **Navid B. Saleh:**

Conceptualization, Supervision, Data curation, Writing - review & editing.

Declaration of competing interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Acknowledgments

This research is partially supported by the National Science Foundation (Award#1805958) and the ConTEX program, a joint funding mechanism between the University of Texas System and the Consejo Nacional de Ciencia y Tecnología (CONACYT) of Mexico (Award#2019-32A). The opinions expressed are those of the authors and do not represent the views of these funding agencies. The authors are grateful to Lionel and Juanita Lopez of the South Texas Colonia Initiative for their assistance in selecting *colonias* for this study. The authors thank the *colonias* residents for their cooperation with community visits and water sampling.

Appendix A. Supplementary data

Additional data, programming code, and details are outlined in the supplemental material document. Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.140111>.

References

- Alfredo, K.A., Lawler, D.F., Katz, L.E., 2014. Fluoride contamination in the Bongo District of Ghana, West Africa: geogenic contamination and cultural complexities. *Water Int.* 39, 486–503. <https://doi.org/10.1080/02508060.2014.926234>.
- Allevi, R.P., Krometis, L.A.H., Hagedorn, C., Benham, B., Lawrence, A.H., Ling, E.J., Ziegler, P.E., 2013. Quantitative analysis of microbial contamination in private drinking

- water supply systems. *J. Water Health* 11, 244–255. <https://doi.org/10.2166/wh.2013.152>.
- Anderson, M.W., 2008. Cities inside out: race, poverty, and exclusion at the urban fringe. *UCLA Law Rev.* 55, 1095–1160.
- Appleyard, S.J., Angeloni, J., Watkins, R., 2006. Arsenic-rich groundwater in an urban area experiencing drought and increasing population density, Perth, Australia. *Appl. Geochem.* 21, 83–97. <https://doi.org/10.1016/j.apgeochem.2005.09.008>.
- Arnade, L.J., 1999. Seasonal correlation of well contamination and septic tank distance. *Ground Water* 37, 920–923.
- Ayotte, J.D., Belaval, M., Olson, S.A., Burrow, K.R., Flanagan, S.M., Hinkle, S.R., Lindsey, B.D., 2015. Factors affecting temporal variability of arsenic in groundwater used for drinking water supply in the United States. *Sci. Total Environ.* 505, 1370–1379. <https://doi.org/10.1016/j.scitotenv.2014.02.057>.
- Bennett, H.B., Shantz, A., Shin, G., Sampson, M.L., Meschke, J.S., 2010. Characterisation of the water quality from open and rope-pump shallow wells in rural Cambodia. *Water Sci. Technol.* 61, 473–479. <https://doi.org/10.2166/wst.2010.817>.
- Bian, X., Gong, H., Wang, K., 2018. Pilot-scale hydrolysis-aerobic treatment for actual municipal wastewater: performance and microbial community analysis. *Int. J. Environ. Res. Public Health* 15. <https://doi.org/10.3390/ijerph15030477>.
- Bondur, R., Cloutier, V., Rosa, E., Benzaazoua, M., 2016. A review and evaluation of the impacts of climate change on geogenic arsenic in groundwater from fractured bedrock aquifers. *Water Air Soil Pollut.* 227. <https://doi.org/10.1007/s11270-016-2936-6>.
- Burton, E.D., Bush, R.T., Sullivan, L.A., Johnston, S.G., Hocking, R.K., 2008. Mobility of arsenic and selected metals during re-flooding of iron- and organic-rich acid-sulfate soil. *Chem. Geol.* 253, 64–73. <https://doi.org/10.1016/j.chemgeo.2008.04.006>.
- Burton, E.D., Johnston, S.G., Kocar, B.D., 2014. Arsenic mobility during flooding of contaminated soil: the effect of microbial sulfate reduction. *Environ. Sci. Technol.* 48, 13660–13667. <https://doi.org/10.1021/es503963k>.
- Casteel, M.J., Sobsey, M.D., Mueller, J.P., 2006. Fecal contamination of agricultural soils before and after hurricane-associated flooding in North Carolina. *J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng.* 41, 173–184. <https://doi.org/10.1080/10934520500351884>.
- Chen, J., 2018. Package ‘GUniFrac’. R-Project.
- Chen, A.S.C., Tien Shiao, H., Wang, L., 2010. Arsenic Removal from Drinking Water by Adsorptive Media U.S. EPA Demonstration Project at Taos, NM. Performance Evaluation Report.
- Cheng, Z., Van Geen, A., Seddique, A.A., Ahmed, K.M., 2005. Limited temporal variability of arsenic concentrations in 20 wells monitored for 3 years in Araihaaz, Bangladesh. *Environ. Sci. Technol.* 39, 4759–4766. <https://doi.org/10.1021/es048065f>.
- Collins, T.W., 2009. The production of unequal risk in hazardscapes: an explanatory frame applied to disaster at the US-Mexico border. *Geoforum* 40, 589–601. <https://doi.org/10.1016/j.geoforum.2009.04.009>.
- Cooper, J.A., Loomis, G.W., Amador, J.A., 2016. Hell and high water: diminished septic system performance in coastal regions due to climate change. *PLoS One* 11, 1–18. <https://doi.org/10.1371/journal.pone.0162104>.
- Didier, G., Heibl, C., Jones, B., 2019. Package ‘ape’. R-Project.
- Durst, N.J., 2019. Informal and ubiquitous: colonias, premature subdivisions and other unplanned suburbs on America's urban fringe. *Urban Stud.* 56, 722–740. <https://doi.org/10.1177/0042098018767092>.
- Durst, N.J., Sullivan, E., 2019. The contribution of manufactured housing to affordable housing in the United States: assessing variation among manufactured housing tenures and community types. *Hous. Policy Debate*, 1–19. <https://doi.org/10.1080/10511482.2019.1605534>.
- Durst, N.J., Ward, P.M., 2016. Colonia housing conditions in model subdivisions: a déjà vu for policy makers. *Hous. Policy Debate* 26, 316–333. <https://doi.org/10.1080/10511482.2015.1068826>.
- Durst, N.J., Johnson, L.B., Ward, P.M., 2014. Measuring self-help home improvements in Texas colonias: a ten year “snapshot” study. *Urban Stud.* 51, 2143–2159. <https://doi.org/10.1177/0042098013506062>.
- FEMA, 2015. Frequency of Flood Events by County: 1996–2013. [WWW Document]. URL <https://community.fema.gov/hazard/flood/be-smart>.
- Fong, T.-T.T., Mansfield, L.S., Wilson, D.L., Schwab, D.J., Molloy, S.L., Rose, J.B., 2007. Massive microbiological groundwater contamination associated with a waterborne outbreak in Lake Erie, South Bass Island, Ohio. *Environ. Health Perspect.* 115, 856–864. <https://doi.org/10.1289/ehp.9430>.
- Fothergill, A., Peek, L.A., 2004. Poverty and disasters in the United States: a review of recent sociological findings. *Nat. Hazards* 32, 89–110. <https://doi.org/10.1023/B: NHAZ.0000026792.76181.d9>.
- García-Prieto, J.C., Cachaza, J.M., Pérez-Galende, P., Roig, M.G., 2012. Impact of drought on the ecological and chemical status of surface water and on the content of arsenic and fluoride pollutants of groundwater in the province of Salamanca (Western Spain). *Chem. Ecol.* 28, 545–560. <https://doi.org/10.1080/02757540.2012.686608>.
- Garrity, G., Brenner, D.J., Krieg, N.R., Staley, J.R., 2002. *Bergey's Manual of Systematic Bacteriology: The Proteobacteria*. Springer.
- Glenn, S.M., Lester, L.J., 2010. An analysis of the relationship between land use and arsenic, vanadium, nitrate and boron contamination in the Gulf coast aquifer of Texas. *J. Hydrol.* 389, 214–226. <https://doi.org/10.1016/j.jhydrol.2010.06.002>.
- Gowrisankar, G., Chelliah, R., Ramakrishnan, S.R., Elumalai, V., Dhanamadhavan, S., Brindha, K., Antony, U., Elango, L., 2017. Data descriptor: chemical, microbial and antibiotic susceptibility analyses of groundwater after a major flood event in Chennai. *Sci. Data* 4, 1–13. <https://doi.org/10.1038/sdata.2017.135>.
- Hargrove, W.L., Juárez-Carillo, P.M., Koc, M., 2015. Healthy Vinton: a health impact assessment focused on water and sanitation in a small rural town on the U.S.-Mexico border. *Int. J. Environ. Res. Public Health* 12, 3864–3888. <https://doi.org/10.3390/ijerph120403864>.
- Housing Assistance Council, 2012. *Taking Stock: Rural People, Poverty, and Housing in the 21st Century*.
- Hynds, P.D., Misstear, B.D., Gill, L.W., 2012. Development of a microbial contamination susceptibility model for private domestic groundwater sources. *Water Resour. Res.* 48, 1–13. <https://doi.org/10.1029/2012WR012492>.
- Jin, Z., Lv, C., Zhao, M., Zhang, Y., Huang, X., Bei, K., Kong, H., Zheng, X., 2018. Black water collected from the septic tank treated with a living machine system: HRT effect and microbial community structure. *Chemosphere* 210, 745–752. <https://doi.org/10.1016/j.chemosphere.2018.07.082>.
- Kim, H., Kaown, D., Mayer, B., Lee, J.Y., Hyun, Y., Lee, K.K., 2015. Identifying the sources of nitrate contamination of groundwater in an agricultural area (Haeam basin, Korea) using isotope and microbial community analyses. *Sci. Total Environ.* 533, 566–575. <https://doi.org/10.1016/j.scitotenv.2015.06.080>.
- Knab, B.R., 2016. Infectious Disease and the South Texas Colonias. University of Texas at Austin <https://repositories.lib.utexas.edu/handle/2152/44560>.
- Kostyla, C., Bain, R., Cronk, R., Bartram, J., 2015. Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Sci. Total Environ.* 514, 333–343. <https://doi.org/10.1016/j.scitotenv.2015.01.018>.
- Kusenbach, M., Simms, J.L., Tobin, G.A., 2010. Disaster vulnerability and evacuation readiness: coastal mobile home residents in Florida. *Nat. Hazards* 52, 79–95. <https://doi.org/10.1007/s11069-009-9358-3>.
- Latin American Housing Network, 2009. A research network for third generation housing policies in consolidated low-income settlements. [WWW Document]. URL <http://www.lahn.utexas.org/TexasColonias.html>, Accessed date: 26 November 2019.
- Leber, J., Rahman, M., Ahmed, K.M., Mailloux, B., Van Geen, A., 2011. Contrasting influence of geology on *E. coli* and arsenic in aquifers of Bangladesh. *Ground Water* 49, 111–123. <https://doi.org/10.1111/j.1745-6584.2010.00689.x>.
- Lozupone, C.A., Knight, R., 2005. UniFrac: a new phylogenetic method for comparing microbial communities. *Appl. Environ. Microbiol.* 71, 8228–8235. <https://doi.org/10.1128/AEM.71.12.8228>.
- MacTavish, K.A., 2007. The wrong side of the tracks: social inequality and mobile home park residence. *Community Dev.* 38, 74–91. <https://doi.org/10.1080/15575330709490186>.
- Martinez, G., Pachepsky, Y.A., Whelan, G., Yakirevich, A.M., Guber, A., Gish, T.J., 2014. Rainfall-induced fecal indicator organisms transport from manured fields: model sensitivity analysis. *Environ. Int.* 63, 121–129. <https://doi.org/10.1016/j.envint.2013.11.003>.
- McMurdie, P.J., Holmes, S., 2013. Phyloseq: an R package for reproducible interactive analysis and graphics of microbiome census data. *PLoS One* 8, 1–11. <https://doi.org/10.1371/journal.pone.0061217>.
- Meays, C.L., Broersma, K., Nordin, R., Mazumder, A., 2004. Source tracking fecal bacteria in water: a critical review of current methods. *J. Environ. Manag.* 73, 71–79. <https://doi.org/10.1016/j.jenvman.2004.06.001>.
- Msilimba, G., Wanda, E.M.M., 2013. Microbial and geochemical quality of shallow well water in high-density areas in Mzuzu City in Malawi. *Phys. Chem. Earth* 66, 173–180. <https://doi.org/10.1016/j.pce.2013.07.002>.
- Muehe, E.M., Wang, T., Kerl, C.F., Planer-Friedrich, B., Fendorf, S., 2019. Rice production threatened by coupled stresses of climate and soil arsenic. *Nat. Commun.* 10, 1–10. <https://doi.org/10.1038/s41467-019-12946-4>.
- NCBI, 2019. National Center for Biotechnology Information [WWW Document]. URL <https://www.ncbi.nlm.nih.gov/>, Accessed date: 15 May 2019.
- NOAA, 2019. National Centers for Environmental Information [WWW Document]. URL <https://www.ncdc.noaa.gov/>, Accessed date: 21 May 2019.
- Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., Mcglinn, D., Minchin, P.R., O'hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Szoecs, E., Maintainer, H.W., 2019. Package “vegan”.
- Olmedo, C., Ward, P.M., 2016. Model subdivisions: the new face of developer lot sales for low-income colonia-type housing in Texas. *Land Use Policy* 52, 181–194. <https://doi.org/10.1016/j.landusepol.2015.12.003>.
- Pang, L., Close, M., Goltz, M., Sinton, L., Davies, H., Hall, C., Stanton, G., 2004. Estimation of septic tank setback distances based on transport of *E. coli* and F-RNA phages. *Environ. Int.* 29, 907–921. [https://doi.org/10.1016/S0160-4120\(03\)00054-0](https://doi.org/10.1016/S0160-4120(03)00054-0).
- Park, J.H., Duan, L., Kim, B., Mitchell, M.J., Shibata, H., 2010. Potential effects of climate change and variability on watershed biogeochemical processes and water quality in Northeast Asia. *Environ. Int.* 36, 212–225. <https://doi.org/10.1016/j.envint.2009.10.008>.
- Pierce, G., Gonzalez, S.R., 2017. Public drinking water system coverage and its discontents: the prevalence and severity of water access problems in California's mobile home parks. *Environ. Justice* 10, 168–173. <https://doi.org/10.1089/env.2017.0006>.
- Podosokorskaya, O.A., Bonch-Osmolovskaya, E.A., Novikov, A.A., Kolganova, T.V., Kublanov, I.V., 2013. Ornatinella apprima gen. nov., sp. nov., a cellulolytic representative of the class Anaerolineae. *Int. J. Syst. Evol. Microbiol.* 63, 86–92. <https://doi.org/10.1099/ijs.0.041012-0>.
- Pritchard, M., Mkandawire, T., O'Neill, J.G., 2007. Biological, chemical and physical drinking water quality from shallow wells in Malawi: case study of Blantyre, Chiradzulu and Mulanje. *Phys. Chem. Earth* 32, 1167–1177. <https://doi.org/10.1016/j.pce.2007.07.013>.
- Pritchard, M., Mkandawire, T., O'Neill, J.G., 2008. Assessment of groundwater quality in shallow wells within the southern districts of Malawi. *Phys. Chem. Earth* 33, 812–823. <https://doi.org/10.1016/j.pce.2008.06.036>.
- Raina, P., Pollari, F., Teare, G., Goss, M., Barry, D., Wilson, J., 1999. The relationship between *E. coli* indicator bacteria in well-water and Gastrointestinal Illnesses in Rural Families. *Can. J. Public Heal.* 90, 172–175. <https://doi.org/10.1007/BF03044501>.
- RDP, 2016. Ribosomal Database Project [WWW Document]. URL <http://www.rdp.cme.msu.edu/>, Accessed date: 5 January 2019.

- Rios, J., Meyer, P.S., 2009. What do toilets have to do with it? Health, the environment, and the working poor in rural South Texas colonias. *Online J. Rural Res. Policy* 4, 1–20.
- Roberts, L.C., Hug, S.J., Dittmar, J., Voegelin, A., Kretzschmar, R., Wehrli, B., Cirpka, O.A., Saha, G.C., Ashraf Ali, M., Borhan Badruzzaman, A.M., 2009. Arsenic release from paddy soils during monsoon flooding. *Nat. Geosci.* 3. <https://doi.org/10.1038/NGE0723>.
- Rodríguez, R., Ramos, J.A., Armienta, A., 2004. Groundwater arsenic variations: the role of local geology and rainfall. *Appl. Geochem.* 19, 245–250. <https://doi.org/10.1016/j.apgeochem.2003.09.010>.
- Rowles III, L.S., Hossain, A., Aggarwal, S., Kirisits, M.J., Saleh, N.B., 2019. Water quality and associated microbial ecology in selected Alaskan native communities: challenges in off-the-grid water supplies. *Sci. Total Environ.* <https://doi.org/10.1016/j.scitotenv.2019.134450>.
- Ryker, S.J., 2001. Mapping arsenic in groundwater—a real need, but a hard problem. *Geotimes Newsmag. Earth Sci.* 46, 34–36.
- Smith, R., Knight, R., Fendorf, S., 2018. Overpumping leads to California groundwater arsenic threat. *Nat. Commun.* 9, 1–6. <https://doi.org/10.1038/s41467-018-04475-3>.
- STCI, 2018. South Texas Colonia Initiative [WWW Document]. Pers. Communication. URL: <https://southtexascolonia.weebly.com/>, Accessed date: 20 August 2006.
- Stroud, J.L., Norton, G.J., Islam, M.R., Dasgupta, T., White, R.P., Price, A.H., Meharg, A.A., McGrath, S.P., Zhao, F.-J., 2011. The dynamics of arsenic in four paddy fields in the Bengal delta spatial variations of arsenic concentrations in paddy soil and waters do not correlate to within-field variations of arsenic concentrations in rice grain. *Environ. Pollut.* 159, 947–953. <https://doi.org/10.1016/j.envpol.2010.12.016>.
- Sullivan, E., 2018. *Manufactured Insecurity: Mobile Home Parks and Americans' Tenuous Right to Place*. First Edit. ed. .
- Takahashi, Y., Minamikawa, R., Hattori, K.H., Kurishima, K., Kihou, N., Yuita, K., 2004. Arsenic behavior in paddy fields during the cycle of flooded and non-flooded periods. *Environ. Sci. Technol.* 38, 1038–1044. <https://doi.org/10.1021/es034383n>.
- Texas Administrative Code, 1976. Title 25 Part 1 Chapter 265 Subchapter F Rule 265.82.
- The Attorney General of Texas, n.d. Colonias Database [WWW Document]. URL <https://www.texasattorneygeneral.gov/divisions/colonias>.
- U.S. Department of Health and Human Services, 2000. *Health on the US-Mexico Border: Past, Present and Future: A Preparatory Report to the Future United States-Mexico Border Health Commission*.
- United States Environmental Protection Agency, 2004. *Understanding the Safe Drinking Water Act*.
- US EPA, n.d. Enforcement and Compliance History Online [WWW Document]. URL <https://echo.epa.gov/>.
- Van Geen, A., Ahmed, K.M., Akita, Y., Alam, M.J., Culligan, P.J., Emch, M., Escamilla, V., Feighery, J., Ferguson, A.S., Knappett, P., Layton, A.C., Mailloux, B.J., McKay, L.D., Mey, J.L., Serre, M.L., Streatfield, P.K., Wu, J., Yunus, M., 2011. Fecal contamination of shallow tubewells in Bangladesh inversely related to arsenic. *Environ. Sci. Technol.* 45, 1199–1205. <https://doi.org/10.1021/es103192b>.
- Ward, P., 2014. The reproduction of informality in low-income self-help housing communities. *The Informal American City*. MIT Press, pp. 59–77. <https://doi.org/10.7551/mitpress/9613.003.0006>.
- Ward, P.M., Peters, P.A., 2007. Self-help housing and informal homesteading in peri-urban America: settlement identification using digital imagery and GIS. *Habitat Int* 31, 205–218. <https://doi.org/10.1016/j.habitatint.2007.02.001>.
- Weber, F.A., Hofacker, A.F., Voegelin, A., Kretzschmar, R., 2010. Temperature dependence and coupling of iron and arsenic reduction and release during flooding of a contaminated soil. *Environ. Sci. Technol.* 44, 116–122. <https://doi.org/10.1021/es902100h>.
- Whitman, W.B., 2009. Bergey's manual of systematic bacteriology: the Firmicutes. *Int. J. Pediatr. Otorhinolaryngol.* <https://doi.org/10.1016/j.ijporl.2011.05.009>.
- Won, G., Gill, A., Lejeune, J.T., 2013. Microbial quality and bacteria pathogens in private wells used for drinking water in northeastern Ohio. *J. Water Health* 11, 555–562. <https://doi.org/10.2166/wh.2013.247>.