



Karst aquifers and water resource contamination in Haiti

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Abstract

Shallow alluvial and karst aquifers and widespread inadequate sanitation practices combine to impact water resources in Haiti. The vulnerability of aquifers is complicated by complex cultural, ecological, geological, hydrological, and hydrogeological considerations. Roughly 84% of the rocks exposed in Haiti consist of calcareous rocks and alluvium. These lithologies serve as an efficient reservoir and transport mechanism for water-borne pathogens, which negatively impact the health of many Haitians. Data from 9,837 water points indicate that 75% of the water sources in the Centre, 55% in the Nord (North), and 12% in the Ouest (West) departments are considered unsafe or high risk based on World Health Organization standards. Inadequate sanitation and, in some cases, improper siting and installation of pit latrines contribute to poor water quality. Numerous safe-water intervention technologies exist and are effective at removing pathogens that contaminate water sources; however, many Haitians lack the means to obtain these solutions. Future regional precipitation and climate trends will have important implications for selecting appropriate water sources and safe-water interventions. Additional efforts to collect and compile regional water quality data are needed to better understand country-wide contamination trends and patterns.

Keywords Haiti · Karst · micro-organisms · Developing countries · Sustainability

Introduction

Haiti, a country of approximately 11 million people, occupies the western one-third of the island of Hispaniola in the Caribbean (Fig. 1). Haiti was a productive and lucrative colony of France until plantation slaves rebelled and gained their independence in 1804. Post-colonial governance and land ownership, combined with internally and externally imposed economic isolation, have resulted in a large number of subsistence farmers working small plots of land. The majority of these small holdings lack sanitation or water irrigation infrastructure and are often used for grazing livestock and charcoal production (Ghilardi et al. 2018).

The Haiti earthquake of January 2010 and rapid post-earthquake emergence of cholera (*Vibrio cholerae*) focused

renewed attention on water resources in Haiti, as well as the endemic problems with sanitation and pathogen transmission in shallow aquifers, springs, and surface waters. The medical community and those who have researched water in Haiti are engaged in ongoing discussions about how best to combat cholera and other water-borne pathogens. One issue is whether to invest scarce resources in vaccination and medical treatment or to invest in longer-term improvements through environmental restoration, sanitation, and safe-water interventions such as filters and other water treatments options (Butler 2011; Cyranoski 2011; Farmer and Ivers 2012; Periago et al. 2012; Piarroux et al. 2011; Wampler 2011).

Poor sanitation practices, combined with shallow aquifers and fractured rocks, result in widespread contamination of shallow groundwater, springs, and surface-water sources (Balthazard-Accou et al. 2017; Gelting et al. 2013; Rebaudet et al. 2017; Schram and Wampler 2018; Wampler and Sisson 2011). Loss of soil, forest cover, and primary forest have led to dysfunctional macro- and micro-biotic ecosystems contributing to a cycle of ineffective contaminant removal and recontamination with pathogens after rain events (Churches et al. 2014; Hedges et al. 2018; Wampler et al. 2019). It is clear that any water resource and sanitation solutions implemented in Haiti need to be transdisciplinary, with a good understanding

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Fig. 1 Study area location map showing major cities and administrative departments in Haiti

of the complex culture, ecology, geology, hydrology, and hydrogeology which impact water quality in Haiti (Wampler et al. 2016).

Most areas in Haiti lack sanitation facilities, and in many rural areas, large-scale safe-water infrastructure and sanitation improvements are not feasible. As a result, many nongovernmental organizations (NGOs) are choosing to direct efforts toward point of use (POU), household water treatment (HWT), and pit latrine installations (Rayner et al. 2016; Widmer et al. 2014). Most of these solutions require continued support, education, and maintenance to remain effective (Lask et al. 2015, Mukherjee et al. 2016, Sisson et al. 2013a, b). Although some improvements in sanitation and water have been made in Haiti, as of 2017, 36% of the rural population still practice open defecation and 40% are using unimproved water sources resulting in widespread transmission of water-borne pathogens and poor health outcomes (Table 1).

Abundant water borne pathogens, poor sanitation, and karst aquifer pathways providing rapid and unattenuated contamination transmission, represent a unique and deadly combination for Haitians. This report provides an overview of the geology, hydrogeology, karst processes, and karst landforms in Haiti and their contributions to contaminated water resources. Water quality data from the Artibonite, Nord (north),

Ouest (west), and Centre departments of Haiti are presented. Several safe-water interventions are evaluated in terms of cost, sustainability, and compatibility. Recommendations are provided for future deployment and support of safe-water interventions which are culturally compatible and sustainable for Haiti.

Geologic setting and hydrogeology

The island on which Haiti is located, Hispaniola, is a mountainous and tectonically active island with folded rocks, earthquakes, and uplifted coral reefs and submarine basalt (Possee et al. 2019; Wang et al. 2018). Complex folding, faulting, mountain building, and brittle deformation of the rocks in much of Haiti is the results of transpressional forces between the North American and Caribbean tectonic plates, extending and dissecting the island (Wang et al. 2018). The deadly earthquake of January 2010 and recent earthquake of 14 August 2021, are reminders of the active tectonic forces that are still shaping the island of Hispaniola (Bilham 2010; Dupuy 2010; Farmer 2012; Kaya et al. 2011; Mercier de Lépinay et al. 2011; Shan et al. 2011; Sheller et al. 2014).

The geology of Hispaniola consists of a core of intrusive igneous rocks which forms the backbone of the island, near the northern border between Haiti and the Dominican

Table 1 Multiple Indicator Cluster Survey (MIC) data for rural Haiti—UN DESA Population Division World Population Prospects (2017) and World Urbanization Prospects (2018)

Year	Population (thousands)	Urban population %	Open defecation %	Unimproved water sources %
1990	7,108	29	62	59
2000	8,648	36	56	51
2008	9,876	47	49	45
2017	10,981	54	36	40

Republic. This core is surrounded by uplifted and deformed sedimentary limestones and shales, volcanic and volcanoclastic rocks, and valley-filling alluvium in a series of roughly east–west-trending mountain ranges (Fig. 2). The details of the geology of Haiti have been well described by previous researchers (Hadden and Minson 2010; Jones 1918; Maurrasse 1982; Woodring et al. 1924). This report will focus mainly on the limestone formations, karst features, and the karst aquifers and springs that serve as a primary water source for many rural Haitians.

Bedrock lithologies in Haiti are dominated by calcareous rock units and alluvium which make up roughly 84% of the surface area of Haiti (Table 2). These lithologies often contain shallow unconfined aquifers that are susceptible to

contamination by inadequate sanitation services and by improperly placed or constructed pit latrines.

Many of the durable limestones have fissures and fractures which have been enlarged by dissolution in a process typically referred to as karstification or simply “karst” (Ford and Williams 2013; Kambesis and Despaigne 2019; Fig. 3). Lack of protective soil cover in many parts of Haiti due to deforestation and erosion has made many unconfined karst aquifers particularly vulnerable to contamination with water-borne pathogens (Alscher 2011; Churches et al. 2014; Hedges et al. 2018; Kennedy et al. 2016; Trček 2007; Wampler et al. 2019). Karst development and dissolution is enhanced locally by faulting, folding, and deformation associated with tectonic forces (Wang et al. 2018).

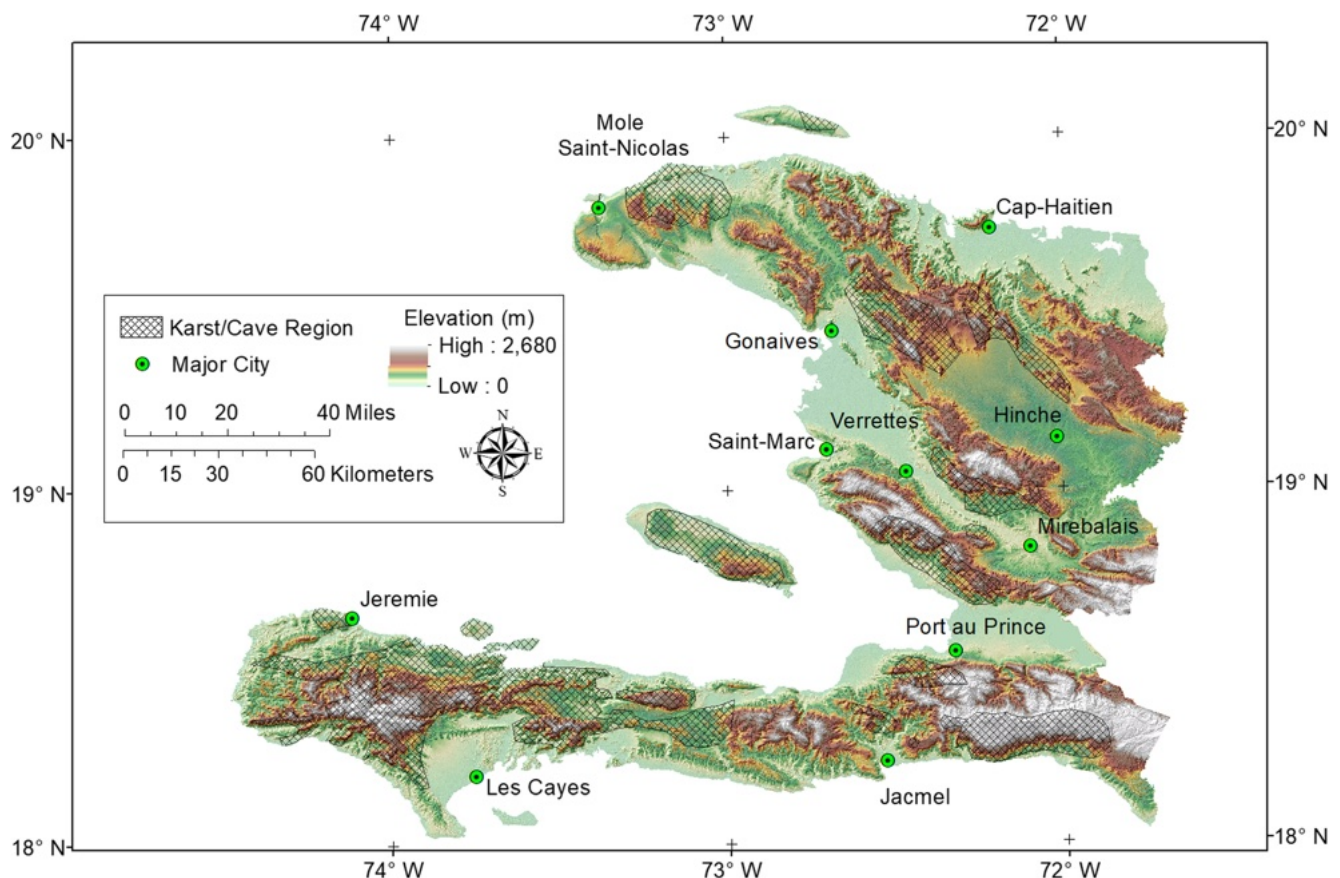
**Fig. 2** Haiti shaded relief map with approximate cave regions in the hachured areas (Cave regions modified from Olivier Testa, personal communication, 2021)

Table 2 Surface area of bedrock lithologies in Haiti. Noncalcareous rock total and calcareous rocks and alluvium totals are italicized

Simplified rock types ^a	Area (km ²)	Area %
Diorites and tonalites	682	2.5
Andesites and rhyodacites	1,195	4.4
Basalt	715	2.6
Ultrabasic rocks	43	0.2
Volcanic rocks	1,696	6.3
Non-calcareous rock total	<i>4,331</i>	<i>16.1</i>
Limestone	8,794	32.6
Marl (carbonate mudstone)	898	3.3
Calcareous flysch	1,740	6.4
Muddy limestone	3,200	11.9
Sandy limestone	2,451	9.1
Alluvium	5,562	20.6
Calcareous rocks and alluvium total	<i>22,644</i>	<i>83.9</i>
Total ^b	26,977	—

^a Lithologies from Centre National de l'Information Géo-Spatiale (CNIGS)

^b Total includes ~1.48 km² of undifferentiated rocks and water

The development of karst dissolution cavities and caves varies considerably in different limestone units with some exhibiting extensive caves and karst conduits, while others have almost no karst or evidence of karst dissolution. No systematic mapping of the cave formations has been identified; however, available mapping suggests there are at least 150 caves located in several regions with greater cave and karst density (Figs. 2 and 4).

In many karst regions, well-developed weathering of limestone and thick soils, collectively referred to as epikarst, serves as an important primary filter for pathogens (Bakalowicz 2004; Trček 2007). Haiti is exceptional in that many limestone outcrops have thin to nonexistent soil cover. Removal of the natural filtration system is primarily the result of erosion, deforestation, and agricultural practices.

Near major rivers, and in the large basin occupied by Port au Prince, sufficient alluvium has accumulated to form alluvial fans and extensive alluvial aquifers and floodplains. These aquifers, although more effective at filtering pathogens than karst limestone, are also prone to contamination from the installation of shallow hand-dug wells in many rural and semiurban settings (Schram and Wampler 2018).

Water resources and climate

Haiti receives a sufficient volume of water each year to support its growing population (Knowles et al. 1999); however, the precipitation that falls on Haiti is not evenly distributed geographically or temporally (Table 3; Fig. 5).

Haiti has two distinct rainy seasons, in May/June and in September/October (Fig. 6). Total precipitation also varies considerably by region with wet and dry seasons more pronounced in some regions than others—for example, in the northwest corner of Haiti near Môle St. Nicholas, the amount and timing of rainfall are significantly different than in Mirebalais, north of Port au Prince (Fig. 6). Observed differences are likely due to a combination of orographic effects and a prevailing wind direction from the east. Regional precipitation differences have important implications for selecting

Fig. 3 Dissolution of limestone along bedding planes and fractures

Fig. 4 Karst cave at Bassim Zim on the central plateau near Hinche



Table 3 Average monthly and total annual precipitation, measured in millimeters, in major cities in Haiti (Centre National de l'Information Géo-Spatiale, 2017). See Fig. 5 for numbered site locations

Site No.	Station	Avg/month precip.	Total precip.
1	Chauffard	212	2,345
2	Kenscoff	191	2,149
3	Léogane	122	1,382
4	Petionville	123	1,373
5	Port au Prince	121	1,361
6	Damien	95	1,073
7	Anse à Galets	82	921
8	Mirebalais	234	2,623
9	St., Marc	77	858
10	Hinche	134	1,484
11	Petite Rivière	129	1,463
12	St. Michel Att	103	1,153
13	Gonaïves	50	564
14	Verrettes	130	1,428
15	Fonds Verrettes	173	1,940
16	Mamelade	158	1,830
17	Ouanaminthe	106	1,213
18	Grande Rivière	115	1,363
19	Gros Morne	105	1,185
20	Bombardopolis	66	781
21	Bassin Bleu	87	1,003
22	Jean-Rabel	79	951
23	Môle Saint Nicolas	48	560
24	Port-de-Paix	100	1,235
25	St. Louis du Nord	147	1,835
26	La Tortue	136	1,738

appropriate water sources and safe-water interventions in different regions of Haiti.

Extensive deforestation and soil loss has resulted in decreased infiltration and aquifer recharge (Alscher 2011; Hernandez-Leal et al. 2006; Reyes-Ortiz et al. 2014). The causes of deforestation are primarily land clearing for agriculture, charcoal production, and urbanization. Decreased natural filtration of surface runoff combined with inadequate sanitation infrastructure, shallow karst aquifers, and dysfunctional macro- and micro-biotic ecosystems, result in widespread contamination of surface-water and groundwater resources with human pathogens (Gerges et al. 2016; Koski-Karell et al. 2016; Rayner et al. 2016; Reyes-Ortiz et al. 2014; Wampler and Sisson 2011). Karst solution of limestone, and abundant fracturing due to brittle deformation, exacerbate this problem by providing pathways, open conduits, storage locations, and rapid transport for bacteria-laden water and organic debris. Biofilms may also be present in underground cavities which allow bacteria and other pathogens to survive in the subsurface and reemerge when groundwater flow increases during the rainy seasons (Dussart-Baptista et al. 2003).

Infrastructure in Haiti is very poor and struggles to support healthy citizens, business development, freedom of movement, and education. Many rural Haitian households and villages do not have running water, power or sanitation. Water resource interventions such as wells, rain water cisterns, spring capping, and reservoirs, are routinely installed by NGOs and local communities; however, maintenance and support for these interventions is often lacking, resulting in failure. Water treatment and storage is also problematic as

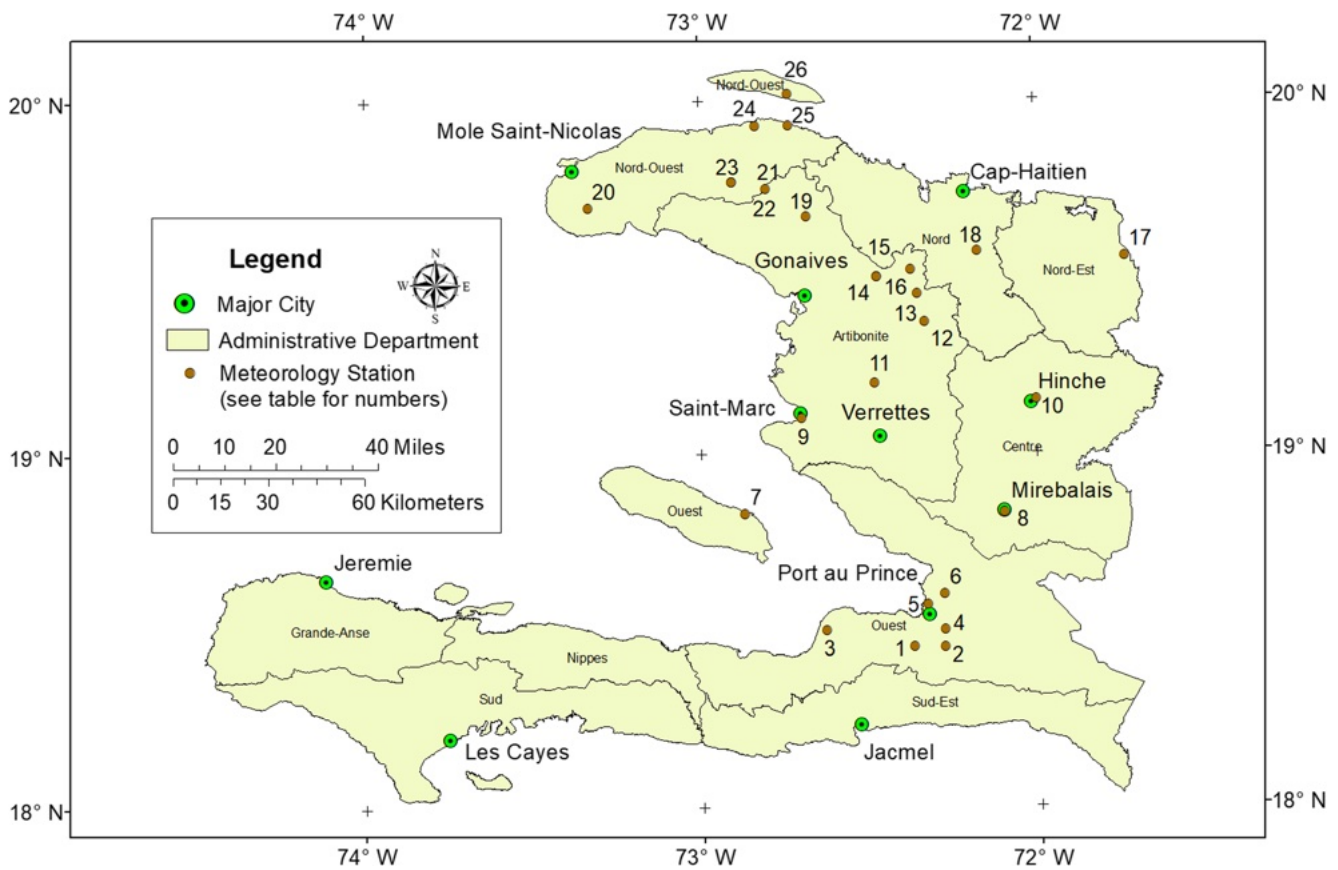


Fig. 5 Map of meteorological stations summarized in Table 3

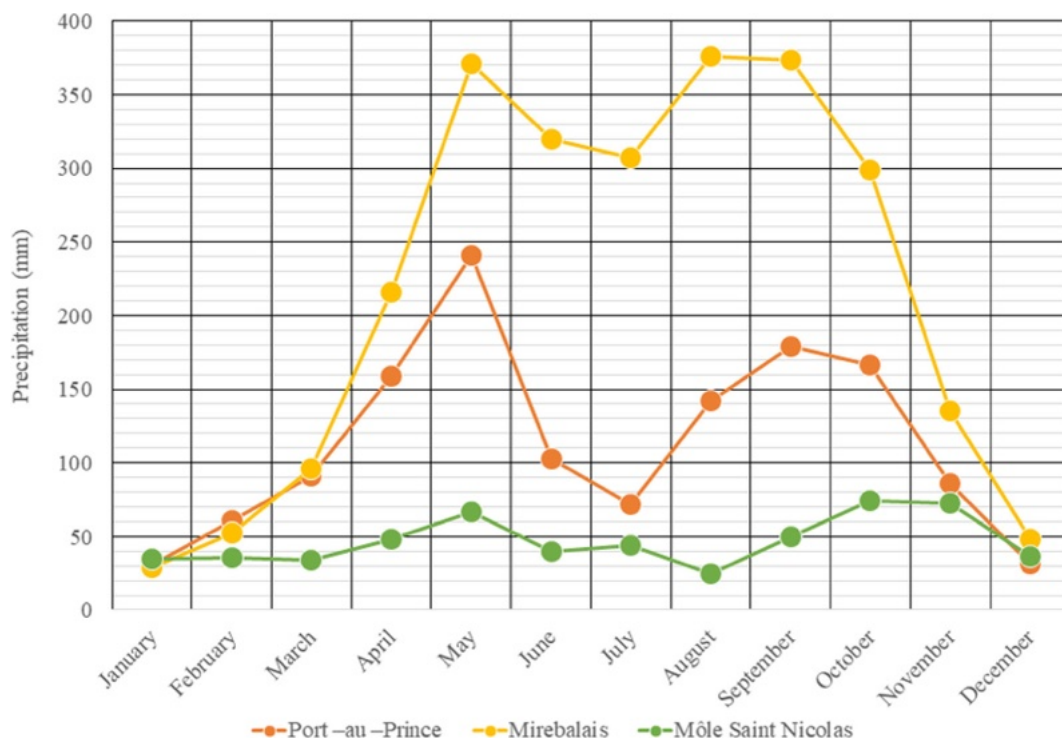


Fig. 6 Monthly precipitation in three Haiti cities showing variation in wet and dry seasons by region—Centre National de l'Information Géo-Spatiale (CNIGS 2008)

most methods employed such as chlorination tablets, biosand filters, fiber membrane filters, and other methods, require regular support to remain sustainable.

Materials and methods

Data for this report were compiled from field measurements collected by research teams, government and NGO, and government sources. Water samples from hand-dug wells in rural Haiti were analyzed using the Colilert method and IDEXX quanti-trays to determine total coliform and *Escherichia coli* (*E. coli*) bacterial contamination (Kinzelman et al. 2005).

Since 2015, the Direction Nationale de l'Eau Potable et de l'Assainissement (DINEPA) and regional teams of workers (Office Régional d'Eau Potable et d'Assainissement (OREPA)) have collected data from water points in an effort to create a comprehensive database. Data format, quality, and availability vary considerably between departments and teams collecting data. Water point inventories were performed by the NGOs Haiti Outreach and World Vision in partnership with OREPA Ouest, OREPA Nord, and OREPA Centre. The water point inventories were performed to facilitate department-level action planning for water and sanitation access. Water quality parameters such as pH, electrical conductivity, and temperature were recorded in the field with an Oakton PCSTestr 35 multi-parameter probe. Flow was

measured using various methods including bucket/stopwatch, area/velocity method for concentrated flows, and in some cases were estimated when direct measurement was not feasible. Aquagenx CBT II EC test kits were used for bacterial analysis on many of the water points; however, some unprotected springs that were not currently used as principal water sources were not analyzed for bacteria.

Results

Data on water sources in Haiti are difficult to obtain. Data collection and analysis methods vary from location to location, making systematic quantitative analysis of water contamination more challenging. Department data, along with original data collected from hand-dug wells and other water sources in rural Haiti provide a partial and imperfect account of groundwater contamination in Haiti.

Water source contamination

Since 2011, water samples from a range of different water sources have been collected and analyzed for *E. coli* in the Artibonite Department near Verrettes, Haiti (Figs. 1 and 7). Water sources sampled include rivers, undeveloped springs, developed springs, hand-dug wells, shallow hand-pump wells, deep wells, water reservoirs, and water treatment systems

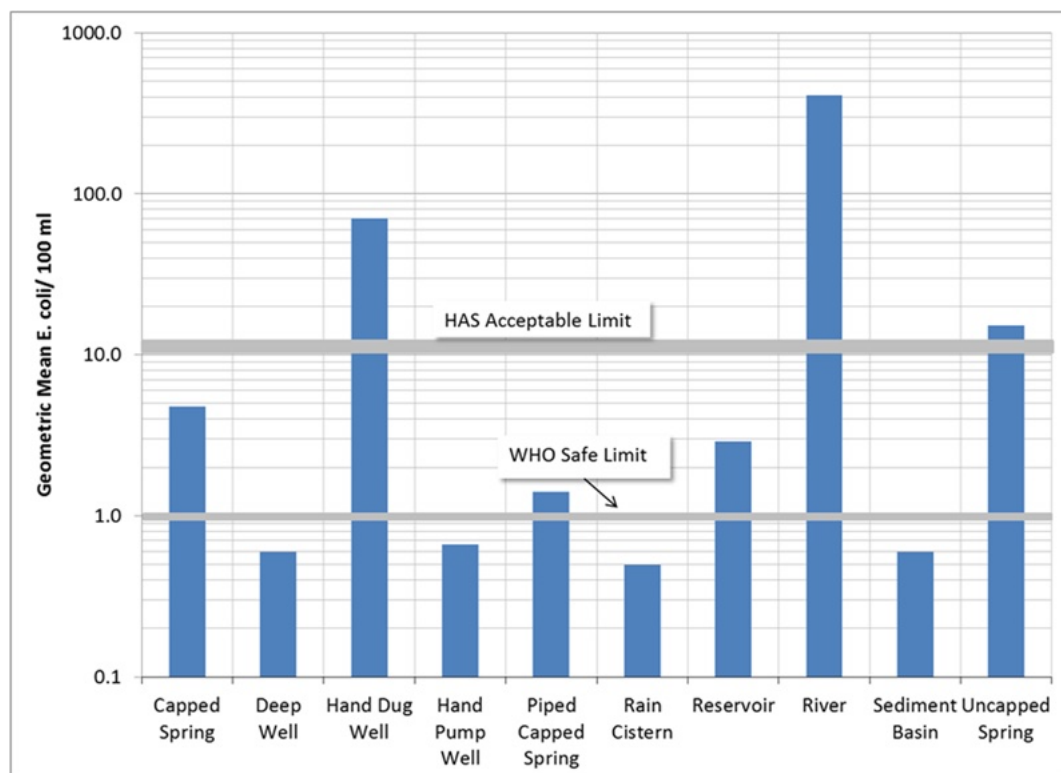


Fig. 7 Summary of *E. coli* values for different water sources near Verrettes, Haiti. The Hôpital Albert Schweitzer (HAS) safe limit is a drinking water standard for a local hospital (10 MPN), and the WHO safe limit (1 MPN) is the World Health Organization drinking water standard

(Figs. 8 and 9). The top three most contaminated water sources are rivers, hand-dug wells, and uncapped or unprotected springs. Twenty hand-dug wells were sampled for bacteria in 2016, with only two of these wells having acceptable *E. coli* levels for drinking water based on World Health Organization Standards (WHO) drinking water standards. The geometric mean of all the wells was 218.8 most probable number (MPN)/100 ml, which is greater than the United States Environmental Protection Agency (US EPA) acceptable body contact standard of 126 cfu/100 ml (Schram and Wampler 2018; US EPA 2012; Table 4).

Aquifer and spring mapping indicate that many rural springs in mountainous areas emerge from alluvial aquifers, carbonate rocks, karst conduits, and cavities. Approximately 75.9% of all mapped springs emerge from alluvial and carbonate aquifers (Table 5).

Department water-point data

Teams from three departments, Ouest, Centre, and Nord, collected and compiled data from 15,581 water points (Table 6). Water sources sampled included borehole or tube wells, piped water sources, protected dug wells, protected springs, rainwater, unprotected dug wells, and unprotected springs. Average conductivity is within a typical range for groundwater with the exception of the Ouest Department, where elevated conductivity may be due to saltwater intrusion into shallow alluvial aquifers. Average groundwater temperature is rather high (Avg. 26.8 °C), which may contribute to pathogen survival in shallow groundwater systems.

A subset of water points (9837) have semiquantitative *E. coli* MPN data determined using the Aquagenx bag method (Aquagenx 2013). This method provides a range of values from 0 to greater than 100 MPN, and has been used to classify the risk of different water sources based on WHO classification (Table 7).

Based on these data, 75% of the water sources in the Centre, 55% in the Nord, and 12% in the Ouest departments are considered unsafe or high risk. Mapping of WHO risk for

4,706 water points in the Centre Department revealed clusters of high-risk water points. This is consistent with clusters of higher population density and inadequate sanitation (Fig. 10).

Discussion

In many developed nations, improved water quality in karst areas is achieved through land-use management laws that provide source water and recharge area protection. However, land management and source water protection, as practiced in many developed nations, may be difficult to implement in Haiti. Laws regulating land-use are rare, especially in rural areas where enforcement and oversight is difficult. Subsistence farmers, although aware of contamination potential near springs, are often less familiar or aware of the need to protect recharge and source-water areas.

The vulnerability and contamination in aquifers and surface water in Haiti make some form of treatment necessary to reduce negative health outcomes for both rural and urban populations. Addressing these water resource challenges will require an informed approach to selecting, implementing, and supporting safe water treatment methods. River contamination with pathogens is likely due to the common practice of bathing and washing clothing in rivers, uncontrolled livestock grazing, and runoff of fecal matter from open defecation into streams. Open defecation and unprotected shallow hand-dug wells are primary contamination sources for unconfined shallow groundwater aquifers. Spring capping is a common practice; however, bacterial contamination in protected springs is only modestly lower than in unprotected springs (Fig. 7). Many hand-dug wells have no surface collars or covers to prevent contaminated runoff from entering the well. Additionally, most of the water collected from hand-dug wells is collected in buckets and other containers which are lowered into the wells on ropes (Fig. 8). These containers, and the ropes used to lower them, are a significant source of contamination. Another potential source of shallow groundwater

Fig. 8 **a** Open hand-dug well common in many small villages. Note the plastic container and rope used to retrieve water. **b** Typical unprotected spring emerging from a shallow limestone aquifer



Fig. 9 Typical concrete spring capping. The spring is covered and spring flow is directed into pipes or distribution systems. Access to the spring capping is typically restricted to a few local leaders



contamination is the installation of unlined pit latrines which can result in leaching of contaminated water into unconfined aquifers and karst systems (Fig. 11). The combination of karst

development and fractures in limestone make site selection and lining of pit toilets critical to preventing shallow aquifer contamination.

Table 4 Hand-dug wells surveyed and evaluated for bacterial contamination in 2016

Site ID	Well depth (m)	Depth to static water level (m)	Depth of water (m)	Coliform MPN ^a	<i>E. coli</i> MPN
060616-01	3.38	2.38	1.00	2,419.6	161.6
060616-02	3	1.66	1.34	2,419.6	148.3
060616-03	2.95	1.95	1.00	2,419.6	143
060616-04	3.4	2.4	1.00	2,419.6	2,419.6
060616-05	2.9	1.78	1.12	2,419.6	579.4
060616-06	2.19	1.55	0.64	2,419.6	686.7
060616-07	2.83	2.33	0.50	2,419.6	185
060616-08	3.02	2.36	0.66	2,419.6	224.7
060616-09	2.68	2.18	0.50	2,419.6	1,553.1
060616-10	ND	ND	ND	2,419.6	1,046.2
060616-11	ND	ND	ND	2,419.6	2,419.6
060616-12	2.75	1.8	0.95	7.5	0.1
060616-13	2.14	1.68	0.46	2,419.6	2,419.6
060616-14	1.62	1.12	0.50	1986.3	83.3
060616-15	3.72	2.24	1.48	2,419.6	461.1
060616-16	2.21	1.45	0.76	2,419.6	727
060616-17	ND	ND	ND	2,419.6	131.4
060616-18	1.93	1.32	0.61	2,419.6	547.5
060616-19	2.24	1.67	0.57	0.5	0.1
060616-20	2.58	0.75	1.83	2,419.6	2,419.6
Arithmetic mean	2.7	1.8	0.9	2,156.4	817.8
Geometric mean	2.6	1.7	0.8	1,174.3	218.8

^a MPN numbers reported as 2,419.6 may be >2,419.6 due to the upper limit of detection

Table 5 Summary of mapped springs and aquifer type compiled from the 1990 hydrologic map of Haiti (Ministère de l'Agriculture 1990)

Aquifer type ^a	No. of springs	Percent of mapped springs
More productive alluvial aquifer	6	1.0
Carbonate aquifers	206	35.2
Karst aquifers	67	11.5
Unconfined alluvial aquifer	141	24.1
Sedimentary formation	24	4.1
Subtotal	444	75.9
Confined alluvial aquifer	9	1.5
Crystalline Formation	132	22.6
Total	585	100

^a Hydrologic units simplified from the Carte Hydrologique Republic D'Haiti (Ministère de l'Agriculture 1990)

Table 6 Water quality measurements from the Ouest, Centre, and Nord departments (see Fig. 1 for department locations)

Department	N ^a	Cond. (μS/cm)	Temp. (°C)	Temp. (°F)	pH	Flow (gpm)	Flow (m ³ /min)
Centre	6,161	517.7	26.9	80.4	7.6	28.1	0.106
Nord	6,949	552.5	26.6	79.9	7.6	31.1	0.118
Ouest	2,471	706.5	27.3	81.1	8.2	18.6	0.070
Combined	15,581	559.3	26.8	80.3	7.7	26.6	0.101

^a Reported *N* value is the total number of water points visited. Not all parameters were measured at each water point

gpm gallons per minute

Spring protection through the installation of concrete capping provides some improvement in water quality, although the amount of protection provided does not usually justify the cost and maintenance required to install and maintain a capped spring (Fig. 9). The primary reason for this is that most springs

in mountainous areas are fed by shallow karst systems which are susceptible to contamination by open defecation, animal waste, and improperly installed pit latrines. Protecting the site where the spring emerges is unlikely to prevent this distal contamination. In-home treatment methods like biosand

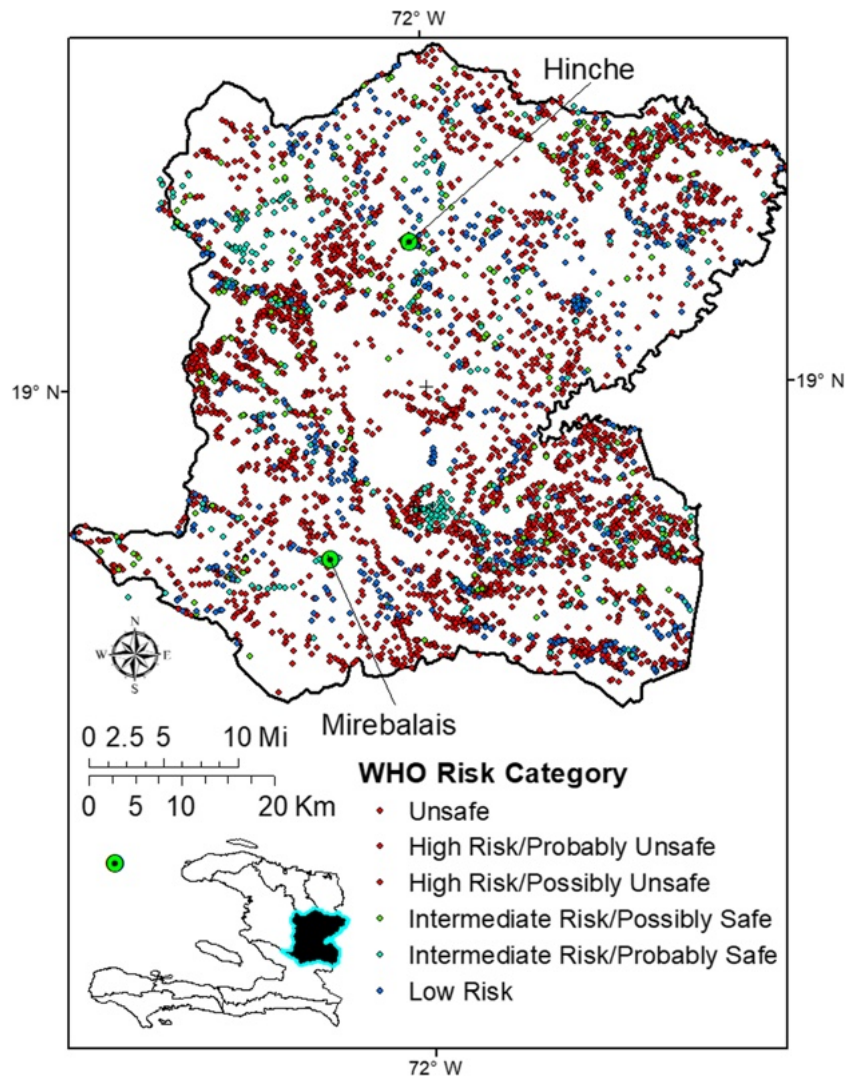
Table 7 Compiled data on water points in three districts in Haiti using the Aquagenx method and WHO risk classification (Aquagenx 2013)

WHO risk level	AquaGenx MPN	No. of water points				
		Centre (%)	Nord (%)	Ouest (%)	Total ^b	Total %
Low risk	0	561 (11.9)	926 (33.4)	1,962 (83.2)	3,449	35.1
Intermediate risk/probably safe	1.0–3.7	380 (8.1)	210 (7.6)	93 (3.9)	683	6.9
Intermediate risk/possibly safe	3.1–9.6 ^a	248 (5.3)	110 (4.0)	28 (1.2)	386	3.9
High risk/possibly unsafe	13.6–17.1	413 (8.8)	228 (8.2)	35 (1.5)	676	6.9
High risk/probably unsafe	32.6–48.3	399 (8.5)	182 (6.6)	48 (2.0)	629	6.4
Unsafe	>100	2,705 (57.5)	1,117 (40.3)	192 (8.1)	4,014	40.8
Total	–	4,706	2,773	2,358	9,837	100

^a The range for “Intermediate risk/possibly safe” as defined by Aquagenx results in overlapping ranges with the “Intermediate risk/probably safe category”

^b Total number of water points was 15,578, but only 9,837 have Aquagenx *E. coli* data

Fig. 10 Aquagenx *E. coli* MPN data for 4,706 water points in the Centre Department. Colors represent different WHO risk levels for water sources as defined by Aquagenx. A total of 6,161 points were visited but 1,455 did not have *E. coli* data



filters, chlorination, fiber-membrane filters (Sawyer), and other point-of-use filtration systems, which can be used and

maintained by each household, are a more sustainable and suitable means of short-term treatment. The suitability of

Fig. 11 Unlined pit latrine located near a home in rural Haiti



specific treatment methods is a function of affordability, life-style compatibility, distance and availability of water sources, and household water needs. Based on the results presented here, there is clearly a need for in-home treatment or other safe-water interventions as well as increased focus on proper sanitation solutions. Longer-term solutions will require ecological restoration and improved land use laws to protect source water and aquifer recharge areas.

Safe and sustainable treatment methods for Haiti

Providing safe and sustainable water in Haiti is complicated by cultural, geologic, ecologic, sociologic, and economic factors which are described subsequently. Those seeking to provide clean water to Haiti must consider and address these factors to successfully and sustainably provide water for Haitians. Near major rivers and in the large basin occupied by Port au Prince, sufficient alluvium has accumulated to form alluvial fans and alluvial aquifers; however, these are subject to contamination by shallow hand-dug wells (Schram and Wampler 2018). Ecological impacts in the form of deforestation, soil erosion, and a habitat destruction contribute to a hydrologic system which is less able to provide natural filtration for pathogens. An often underappreciated player is the microbiotic ecosystem which is an integral part of the macrobiotic ecosystem (trees and plants), which has also been impacted (Dussart-Baptista et al. 2003; Hwang et al. 2014). Both the microbiotic (beneficial water-borne organisms) and macrobiotic provide a first line of defense for protecting groundwater in Haiti from contamination.

Attitudes and perceptions of water in Haiti are affected by religious attitudes, historic practices, and the general educational level of most rural Haitians (Phelps et al. 2017). Many Haitians who practice Voodoo view water and sources of water as sacred. Waterfalls and springs are generally viewed as sacred places in Voodoo for their natural beauty and provision. Catholicism also views water as sacred, but in a way more connected to God and the cleansing power of water. Both of these viewpoints are predisposed to view water as clean and sacred even when it may be contaminated with pathogens that can kill, especially when those pathogens are not visible and the water appears clean. This widespread perception of water as both sacred and safe is a major challenge for those trying to implement safe water interventions in Haiti.

Haiti is an economically challenged country with many facing daily economic and health challenges. Water in large cities is often provided by central systems of fountains or through vendors of treated water in bottles and bags. In the mountains of Haiti, central water systems and bottled water are not widely available, so many drink untreated water from springs. A simple and effective solution for ensuring the safety of this water would be to boil all water consumed, but many do not have the money to buy fuel for sterilizing water and

cooking their meals. Many Haitians are also unaware that the water is unsafe because it looks clean and may be collected from a spring emerging from rock. Numerous water treatment methods are available in Haiti; however, each has pros and cons and may have applicability for some regions more than others (Table 8).

Conclusions and recommendations

Water quality in the shallow unconfined aquifers of Haiti is clearly being impacted by inadequate sanitation infrastructure and practices and, in some cases, improperly installed or located pit latrines. This results in widespread contamination of groundwater with pathogens which negatively impacts the health of many Haitians. POU, HWT, and other water treatment interventions exist; however, many of these solutions require careful selection, education, and follow up to remain sustainable and effective. Climate-change-induced alterations to the already variable precipitation and climate will likely make it more challenging to provide safe and sustainable safe water in Haiti.

The database of water points obtained for this study allowed limited quantitative and qualitative analysis of water contamination at the department level. Similar data are needed across all departments in Haiti so that regional trends can be better understood and reported. Data inconsistencies among departments poses a challenge to this effort. Data will need to be compiled, and quality checked, to ensure that data from different departments are compatible with regional water quality analysis. Regional water quality analysis would be aided by a centralized database into which water quality data could be contributed. Only after widespread collection and compilation of additional data will a country-wide assessment of groundwater contamination be possible. Quantitative bacteriological data, using a method such as the IDEXX Colilert-18, would provide more useful information about bacterial contamination than the semiquantitative Aquagenx bag method. However, the logistics and cost of the IDEXX method may prevent its widespread use.

The distribution, education, and support for POU and HWT options should be decentralized and democratized. This could be achieved through a network of trained resellers operating in a similar manner to the way Digicel Cell Phone company uses “Papa Dap” vendors who resell phone minutes. Each of these independent contractors purchases minutes from Digicel then resells them for a slight profit. This model encourages widespread availability of cell phone minutes, even in rural areas. A similar network of water-treatment-solution vendors could make water treatment tools and support widely available, even in rural areas without NGO intervention or support. Vendor training and support could be offered by local

Table 8 Evaluation of several water treatment methods and technologies with relative costs and sustainability in Haiti

Method	Pros	Cons	Relative cost	Sustainability	Effectiveness
Passive solar disinfection (SODIS)	Cheap; bottles reusable; technology simple	Water is warm; treatment takes 24–48 h; turbidity can reduce effectiveness	\$	High	High
Plastic biosand filters	Lightweight; no chemicals required; may introduce beneficial organisms	Time needed to develop biofilm; skill required to maintain and support; turbid water can clog	\$\$\$	Moderate	Moderate/high
Concrete biosand filters	Can usually be built and maintained with local materials; no chemicals required	Difficult to transport and move; skill required to maintain and support; turbid water can clog	\$\$	Moderate	Moderate/high
Chlorine (powder or tablets)	Very effective when used properly; materials widely available	Bad taste; training and support required; potential negative health impacts; doses vary depending on product being used	\$	High	Low to high
Boiling (3–5 min)	Can be accomplished with local materials and technology	Expensive; contributes to deforestation; cooling water necessary before drinking	\$\$\$	Moderate	High
Reverse osmosis	Proven technology; removes most contaminants both biological and chemical; can remove salts	Very expensive; requires consistent fuel or power; skill required; maintenance required	\$\$\$\$	Low	High
Fiber membrane filters (e.g. Sawyer)	Easy to use and maintain; can be back-flushed to extend life; portability and compact size; scalable	Expensive; clogging in some areas with mineral-laden water; turbid water can clog; improper backwashing can cause contamination	\$\$\$	Moderate	High
Clay filters	Cheap and can be made from local materials; no chemicals required	Clay quality can affect treatment; skill required; may not be effective for some viruses and bacteria	\$	High	Low/moderate
Ultraviolet disinfection	Very effective; power requirements low (~200 watts for 40 gpm)	Flow rates low; installation and maintenance required; bulbs have limited life	\$\$	High/moderate	High
Slow sand filtration	Can be built and maintained with local materials; no chemicals required; scalable	High initial costs; monitoring and maintenance required; turbid water can clog	\$\$	High/moderate	Moderate
Ozone disinfection	Does not create harmful byproducts; no change in taste or residual chemicals	Equipment required is expensive and requires maintenance; ozone is reactive and corrosive	\$\$\$\$	Low	Moderate
In-situ filtration (ISF) wells	Can be constructed with local materials and labor; low maintenance once constructed	Support and maintenance is required by local community members; monitoring required to ensure effective treatment	\$\$	High	Moderate/high

NGOs, DINEPA or OREPA staff, schools, or a combination of these entities.

Biweekly street markets, which take place in most Haitian towns and villages, are a widespread and universal place where Haitians gather to buy and sell food and household items. These markets represent a potentially effective opportunity to distribute, and provide local education and support for POU water-treatment devices. Information and POU products could be provided to market resellers at these community gathering places along with accurate information and support, thus simplifying distribution and support.

Many different strategies and projects to provide safe and sustainable water have been attempted in Haiti, most with limited long-term success. Providing Haitians with inexpensive and readily available POU water treatment at convenient and familiar locations, and in a culturally compatible way, may be the best means of reaching the goal of universal access to clean water in Haiti in the near term. Western-style water treatment infrastructure and water distribution systems,

although perhaps more technologically effective, are simply not culturally or economically compatible with most rural Haitian communities.

Long-term and widespread improvement of groundwater quality in Haiti will require changes in land-use management and agricultural practices to reduce deforestation, erosion, and soil loss. Other long-term solutions include the installation of properly constructed deep wells (>30 m) near populated areas, conversion of hand-dug wells to in-situ filtration wells, development of a network of community-based water experts to support/maintain in-home treatment methods, and ecological restoration and reforestation (Schram and Wampler 2018). Both ecological restoration and widespread reforestation will require changes in the land management, new land-use laws, and enforcement of existing land-use laws.

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Declarations

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