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Chapter

Pollution of Water Resources and Environmental Impacts in Urban Areas of Developing Countries: Case of the City of Les Cayes (Haiti)

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Abstract

Many cities in developing countries are facing serious problems of microbiological quality of their water resources. In this context, chlorination is used as common method of treating water intended for human consumption. However, it has been shown that disinfection by chlorination is ineffective in inactivating *Cryptosporidium* oocysts. Therefore, the physicochemical behavior of *Cryptosporidium* oocysts and geological formation of those areas become an important environmental issue of research. In Haiti, *Cryptosporidium* oocysts have been identified in the groundwater being used for human consumption in Les Cayes. Moreover, cryptosporidiosis is one of the most frequent causes of diarrhea in Haiti. The transfer of *Cryptosporidium* oocysts, through an alluvial formation from Les Cayes (Haiti), was investigated. The aim of this chapter was (i) to review the biological cycle of *Cryptosporidium* and the physicochemical behavior of *Cryptosporidium* oocysts in order (ii) to understand their movement through soils and (iii) to evaluate the chemical conditions and soil characteristics which can constitute factors influencing the retention of oocysts or facilitate their transfer into groundwater.

Keywords: *Cryptosporidium* oocyst, soil, transfer, pollution, groundwater resources, Les Cayes (Haiti)

1. Introduction

Pollution of water resources has become a major environmental challenge for many urban areas in both developed and developing countries [1–3]. Although developing countries are characterized by a lower industrialization, the deficiency observed in solid waste and wastewater management and the lack of city planning constitute factors facilitating the environmental pollution of cities. Moreover, unexpected population growth is related to water quality degradation and is causing large increase in nutrients and microbial loads [4–6]. Therefore, urban areas have the potential that generate environmental impacts at multiple scales [4].

Urbanization often causes environmental degradation and harms human health particularly in developing countries [7].

Due to reasons relating to the economic problems of developing countries, when urban effluents are actually collected, they are most usually discharged into open drainage canals or into septic tanks equipped with infiltration shafts [8]. Infiltration of urban stormwater runoff can be also considered as one of the main factors of the deterioration of soils and groundwater quality [3]. This last is increasingly subject to intensive voluntary discharges of highly polluted effluents, wastewater, and runoff water in urban areas [9]. Studies have shown that in developing countries there is a strong likelihood of a marked correlation between the groundwater contamination in urban areas and the way in which public services operate [10]. In the specific socioeconomical context of developing countries, there is an important challenge of public health related to the possibility of the appearance of biological risk due to the contamination of groundwater resources by pathogenic microorganisms.

In Haiti, oocysts of *Cryptosporidium* have been detected in surface water used as drinking water and in the water supplied by the public water service of Port-au-Prince [11, 12]. In the surrounding region of Cap-Haitien, investigations conducted on water resources revealed the presence of *Cryptosporidium* oocysts in surface and groundwater used by the population for domestic purposes [13, 14]. The number of oocysts detected in the city of Cap-Haitien ranges from 741 to 6088 oocysts per 100 liters of water.

In the city Les Cayes (Haiti) has highlighted the presence of the *Cryptosporidium* oocyst groundwater used by the population for domestic purposes [10, 15, 16]. The number of oocysts detected varied from 5 to 100 per 100 l of water [15]. These results show that the surface water and groundwater of Cayes are contaminated by pollution of fecal origin and are a source of potential biological risk for the health of the population exposed. Human risk assessment due to these results shows in evidence biological risks for consumers that range from 4 to 1274 oocysts per 100 l of water. The management phase of this assessment allows for the questioning of physicochemical mechanisms governing the transfer of oocysts from the ground to underground waters. The objective of this study was to investigate the behavior of *Cryptosporidium* oocysts under physicochemical conditions and soil characteristics in saturated porous media of Les Cayes and to describe the water pollution dynamics of *Cryptosporidium* oocysts.

This work reported in this chapter has four main sections. Initially, we introduce the chapter. The first section proposes a synthesis of information on the biological cycle of *Cryptosporidium*, followed by a review of source and transport of the physicochemical behavior of *Cryptosporidium* oocysts. The second section describes the geography of the City of Les Cayes. It also describes the hydrogeological properties of this city while taking care to underline the management system of wastewater and solid waste developed in that area. The third section presents the chemical conditions and soil characteristics which can constitute factors influencing the retention of oocysts or facilitate their transfer into groundwater. The fourth section is devoted also to sharing results of works on the mobility and retention of *C. parvum* oocysts in soil of the City of Les Cayes.

2. Life cycle of *Cryptosporidium*

2.1 Biological cycle of *Cryptosporidium*

Cryptosporidium represents the genus of a variety of intracellular parasites that infect vertebrates, including humans, worldwide. *Cryptosporidium* belongs

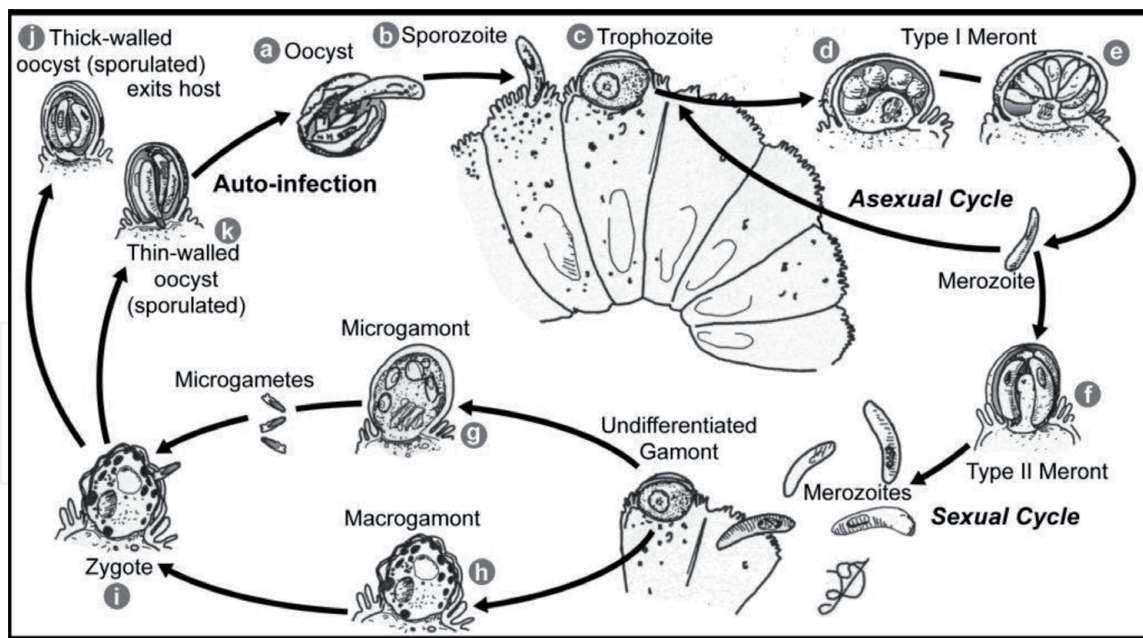


Figure 1. Life cycle of *Cryptosporidium*. Reported in [10]. Source: <http://www.stanford.edu/group/parasites/ParaSites2005/Cryptosporidiosis/index.html>.

to Apicomplexa (synonym Sporozoa), an obligate parasitic group of eukaryotes. However, recent studies, based on genetics and physiology, have now relocated the genus *Cryptosporidium* from Coccidia to *Gregarina*, which includes free-living stages, enabling host-free multiplication, and so may constitute an additional risk factor for human infection [17]. The life cycle of *Cryptosporidium* is monoxenous, which means that every stage in the parasitic cycle's development takes place inside the same host. The multiplication cycle comprises of sexual and asexual stages. The progress of this cycle is schematically depicted in **Figure 1**. The asexual multiplication results in merozoite formation, enabling reinfection of intestinal epithelial cells and the sexual cycle culminating in thin or thick-walled sporozoite-containing oocysts (4–6 μm with an ovoidal or round shape) [18]. Infection occurs when the oocysts are ingested by a suitable host. While in the intestines, the oocyst releases sporozoites which invade the epithelial linings of the intestines or the lungs. The infectious oocysts are passed through the feces and enter the environment. Under natural conditions, fecal matter shelters oocysts from desiccation and increases the impermeability of the wall to small molecules, thereby reducing their exposure to lethal environmental factors [19]. The resistance of oocysts in a solid matrix such as soil has become a crucial parameter in understanding their transfer to lower layers. Oocysts persist longer in soil than in water at the same temperature, with a preference for moist silty soils rather than moist clay or sandy [20]. Oocysts can remain viable and infectious in water for several months at temperatures ranging from 0 to 30°C. Other tests have shown that boiling water can kill *Cryptosporidium* oocysts in less than a minute [21]. The exposure to sunlight had no effect on the viability of *Cryptosporidium* oocysts, but UV at 265 nm and black light at 365 nm lead to a reduction in the number of viable oocysts [22].

2.2 Source and transport of *Cryptosporidium parvum* oocysts through soils

Cryptosporidium is a zoonotic intestinal protozoan parasite that affects the gastrointestinal tract of humans and animals [23, 24]. This protozoan parasite is transmitted via the fecal-oral route and is an important cause of childhood diarrhea and mortality [25]. In developing countries, 8–19% of diarrheal diseases are attributed to

Cryptosporidium [26]. Furthermore, 10% of the population in developing countries excretes oocysts which the scattering and resistant form of *Cryptosporidium* sp. is eliminated with feces [27]. Immunocompetent persons will usually recover from the illness within 2 weeks, whereas immunocompromised individuals, including patients undergoing chemotherapy for cancer, patients with AIDS, infants, children, and elderly, may be afflicted with chronic and debilitating illness [28]. In natural surface water and soil, *Cryptosporidium* oocysts can survive up to 6 months [19, 29]. Oocysts are resistant to a number of environmental stresses, including chlorination during drinking water treatment.

The infectivity oocysts are high, and ingestion of just a single oocyst generates an infection probability [30]. Many outbreaks of foodborne cryptosporidiosis have been described also. In Milwaukee in North America (1993), a massive outbreak of acute diarrhea was caused by drinking water treatment deficiencies; about 403,000 persons were affected and 69 died [31]. According to [32] there have been at least 18 outbreaks of cryptosporidiosis in which foodborne transmission has been epidemiologically implicated, and 8 of these outbreaks were directly linked to consumption of fresh produce [33]. Furthermore, two more foodborne outbreaks (one in Finland and one in the UK) have been published subsequently [34, 35].

Such environmental contamination can be from soil, particularly soil amended with feces or manure, or from water such as irrigation water or wash water along the food chain [36]. Several models have been used to study pathogen transport. Previous work has investigated the transport of *Cryptosporidium* oocysts in terrestrial environments [37, 38]. To remove oocysts from water resources, several mechanisms such as filtration methods [39]; laboratory columns [40, 41] or radial stagnation point flow (RSPF) cell [42, 43] have been used. Otherwise various aspects of *C. parvum* transport and removal in granular porous media have been also examined, such as the influence of solution chemistry, fluid flow rate, and sediment grain size [40]. Detailed experimental observations have since confirmed this to be the case, especially through soil macropores and in karstic geological terrain through fractured bedrocks [44, 45]. Based on experimental evidence, it seems well established that *C. parvum* oocysts can move in soils through preferential pathways in relatively large amounts [46]. The surface properties of the oocyst wall may mediate how it survives and its interactions with chemical and particulate surfaces in the environment. Therefore, changes in the wall may affect adhesion, transport properties, and mobility in natural environments and treatment plants. Oocyst removal in porous media is still poorly understood. The transport of *Cryptosporidium* oocysts in the subsurface environment is of great concern for water quality.

2.3 Surface properties of *Cryptosporidium* oocysts

The *Cryptosporidium* oocysts are spheroidal shapes with a specific gravity of 1.0 g cm^{-3} [47]. *Cryptosporidium* oocysts' wall has three layers. An acidic glycoprotein is hypothesized to make up the outermost layer. The inner layer also appears to be a filamentous glycoprotein, while the central layer is thought to be a rigid, complex lipid [48]. The thickness of the wall and its capacity to strongly adhere to both organic and inorganic surfaces are features that could be attributed to its survival in the environment [49]. Other studies determined on the oocyst surface that it has high contents of the amino acid cysteine, proline, and histidine [50]. Otherwise oocysts have a negative surface charge under typical environmental conditions [51–57], likely due to the presence of carboxylate, carboxylic, and phosphate groups on the oocyst surface [55]. Both steric and electrostatic forces can play a role in oocyst association with suspended particles [58]. The understanding and mastering of the complex sorption

phenomena involve an evaluation of the hydrophobic and electrostatic surface properties of the parasite [50]. Indeed, the surface properties of the oocyst wall may mediate how it survives and its interactions with chemical and particulate surfaces in the environment. Therefore, changes in the wall may affect adhesion, transport properties, and mobility in natural environments. The most important physical and chemical adhesion properties are the surface charge and hydrophobic characteristics [59]. The surface electrokinetic potential is negatively charged with a range from -19 to -42 mV at a neutral pH [60]. However, the negative surface charge increases with decreasing pH, and the hydrophobicity is low with high medium conductivity [48].

2.4 Transport of *Cryptosporidium* oocysts

Deyac et al. [61] elaborated in a working paper based on the data found in literature on the transport of *Cryptosporidium* oocysts. Based on its size, the *C. parvum* oocyst is physically classified as a biological colloid. Surface charges measured by the ξ potential of the oocysts have been found to be neutral to slightly negative in most natural waters. Exact values depend on analytical methods used [50, 62]. Transport and filtration of such colloids in porous media are by advection hydrodynamic dispersion and interactive processes between colloids and solids surfaces [63]. A simple one-dimensional transport model in a steady-state flow field is:

$$\frac{\partial c}{\partial t} + \frac{\rho_b \partial s}{\theta \partial t} = v d \frac{\partial^2 c}{\partial x^2} - v \left(\frac{\partial c}{\partial x} + \lambda c \right) \quad (1)$$

where c is the concentration of *C. parvum* oocysts in suspension, s is the concentration of *C. parvum* oocysts adsorbed reversibly on solid surfaces, ρ_b is bulk density, θ is porosity, d is the hydrodynamic dispersivity coefficient, v is the advective pore velocity, and λ is the colloid filtration coefficient.

It is commonly observed that v in Eq. (1) is larger for colloids than for water (velocity enhancement) [64]. Note that Eq. (1) accounts for permanent deposition (filtration) of colloids through the first-order term $v\lambda c$ as well as for reversible deposition (sorption) through the second term on the left-hand side. Several models have been introduced to describe the permanent removal of colloids by filtration onto the solid phase [65, 66]. Mass balance considerations for the deposition of colloids in a clean packed filter bed of uniform spheres yield the following relationship between the filtration coefficient and the physical properties of filter bed and colloid [66, 67]:

$$\lambda = \frac{3(1-\theta)}{2d_c} \alpha \eta \quad (2)$$

where d_c is the median grain size diameter, α is an empirical constant referred to as collision efficiency, and η is the collector efficiency. Collector efficiency, η , represents attachment to solid surfaces due to colloid advection and diffusion, interception, buoyancy, and London-van der Waals attractive forces. These four characteristics are expressed in dimensionless form by the Peclet number, N_{Pe} ; the interception number, N_R ; the gravitation number, N_G ; and the London-van der Waals constant, N_{Lo} [66]. In addition, a correction factor, A_s , is introduced that accounts for the pore geometry and its impact on packed bed collector efficiency. Rajagopalan and Tien showed that η is then computed from [66, 67]:

$$\eta = 4A_s N_{Pe}^{1/3} N_{Lo}^{-2/3} + A_s N_{Lo} N_R^{1/8} N_G^{15/8} + 0.00338 A_s N_G^{1.2} N_R^{-0.4} \quad (3)$$

For the evaluation of the *C. parvum* transport behavior in column experiments, the collector efficiency, Eq. (3) can be computed a priori from the physical

properties of the pore space (porosity, median grain size, bulk density), from the physical properties of water (density, viscosity, pore velocity) and from the physical properties of the colloid (density, mean diameter, particle diffusion coefficient). The collision efficiency, α , represents an empirical constant to account for the fact that repulsive forces at the collector surface (double-layer repulsion), which are not accounted for in Eq. (3), will prevent a fraction of the colloids from attachment [65, 67].

3. Case study in the city of Les Cayes

Several studies have highlighted the presence of *Cryptosporidium* oocysts in the surface and groundwater of the coastal city of Les Cayes [10, 14, 15]. The city is located at 18°34'00" Northern Latitude and 72°21'00" west Longitude on the Caribbean coast, on a coastal plain with high rainfall (over 2000 mm/year). Hydrogeologically, the basin of Les Cayes includes Plaine des Cayes and its surrounding mountains. They are drained by two principal rivers: Grand Ravine of the South and l'Acul du Sud along with many other secondary rivers. The basins of these two principal rivers are not very wide (65 and 75 km²) but benefit from a very abundant pluviometry which gives them particularly high specific outputs (70 and 55 ls/km²). Their low water output adds up to ~2.5 m³/s. In the case of l'Acul du Sud, this low water output is supported by an important karstic resurgence that drains the calcareous plates forming the southernmost buttresses of Massif de la Hotte's summit, Pic Macaya. Similarly, Ravine du Sud, its principal waterway, has moderate water output of 4.96 m³/s and low water output of 1.31 m³/s. The watershed is shared between three distinct types of aquifers: alluvial aquifers with free waters, karstic aquifers, and carbonate aquifers (fissured and fragmented), from where resurgences and outputs vary [68].

The alluvial aquifer of Plaine des Cayes is, hydrographically speaking, located in the Southwestern area of Haiti. Dominated by Massif de la Hotte which measures more than 2000 m in altitude, this area receives abundant rains at the mountaintops (more than 3000 mm/year) and gradually toward the coasts (1400 mm/year) with an average of 1900 mm/year. The renewable groundwater resources which are sustained through direct rain infiltration are concentrated in massive karstified limestones. Its aquifer constitutes, for the entire region, its most important directly exploitable underground water resource. The depth of the water table exceeds 40 m at the plain's headwaters. In the high and moderate areas, the water table is free. In the low plain, the water table is restricted under an argillaceous covering. It is supplied by abundant and direct rain infiltration (1900 mm/year) on the high and moderate areas of the plain and by discharge from the mountains caused by floods [68].

Several factors play a role in explaining the presence of *Cryptosporidium* oocysts in the groundwaters of major cities in Haiti. These same factors can also be considered to elaborate on the hypotheses relating to the contamination of the city of Les Cayes' nappe. They are (I) urban spaces of the country characterized by the absence of basic services, such that the collection and treatment of wastewater, the collection of solid waste, and the disposal of excreta and (II) the presence of latrines and septic tanks in alluvial and karstic formations and aquifers' recharge zones. This situation can contribute to the contamination of water resources originating from human fecal discharge. (III) In Haiti, the control of water quality which is to be carried out by public agencies is not always assured [69], and (IV) chlorination remains the only mode of treatment applied to raw water intended for human consumption. This is despite the fact that *Cryptosporidium* oocysts are resistant to chlorine.

4. Behavior of *Cryptosporidium* oocysts under chemical conditions in saturated porous media

The contamination of groundwater by *Cryptosporidium* oocysts has been the subject of several studies in which the authors have approached the laboratory on the behavior of *Cryptosporidium* oocysts under chemical conditions in saturated porous media. In order to appreciate the interactions between oocysts and soil (granular porous media) techniques based on the principles of colloid and surface chemistry were used.

4.1 Sources and purification of *C. parvum* oocysts

Viable *Cryptosporidium* oocysts purified using discontinuous saccharose were obtained from the National Institute of Agronomic Research (INRA). The oocysts were collected in fecal samples from naturally infected dairy calves and kept in an aqueous medium. They were stored (in the dark at 4°C) in potassium dichromate. The concentration of oocysts in the stock solution was about 2.0×10^7 oocysts/ml. They were used for laboratory experiments within 10 days of collection.

4.2 Chemical conditions

Batch equilibrium experiments were used to study the effect of chemical condition on the behavior of *Cryptosporidium* oocysts in porous media. These experiments were conducted with two electrolyte solutions: 0.003 M CaCl₂ and 0.001 M NaBr. The Debye-Hückel equation was used Eq. (4):

$$-\log\gamma_x = (0.51\sqrt{I}/1 + 3.3a_x\sqrt{I}) \times Z_x^2 \quad (4)$$

In this equation, α_x represents the diameter of the ion nm, Z_x the charge of the ion, and the ion X is I and the ionic strength of the solution. $\alpha_{Ca} = 0.6$; $\alpha_{Cl} = 0.3$.

4.3 Soil composition

Five points were selected. Each point on a random sample has been taken. The samples were collected manually at a depth between 40 and 80 cm (**Figure 2**). The soil consisted of 35.6% coarse sand, 7.1% fine sands, 25.4% fine silt, 6% coarse silt, and 25.9% clay (**Table 1**). The soils were air-dried at 35°C and sieved (2 mm), which were then stored at room temperature until used. The physicochemical characteristics of soil, such as pH, organic matter, clay, and CaCO₃, and cation exchange capacity (CEC) were measured using standard analytical methods presented in **Table 2** and were determined at the National Laboratory of Building and Public Works (LNBTP) Laboratory Analysis of Soil Arras (INRA) and the Institute for Radiological Protection and Nuclear Safety (IRSN).

4.4 Batch experiments

In the laboratory were added 4 g of soil with a suspension of oocysts in 12 bottles of crystal polystyrene sealed at a ratio of 1:10. To avoid changing the soil properties, the ionic strength of the solutions was adjusted by the addition of a 3 mM solution of calcium chloride (CaCl₂) in 6 of the 12 bottle sand and a 100 mM solution of sodium bromide (NaBr) in the remaining 6. The batch tubes were placed vertically in racks on a vibration-free bench top after mixing to allow particles to settle. These were stirred for 24 h using a shaker table at 220 shakes per minute room

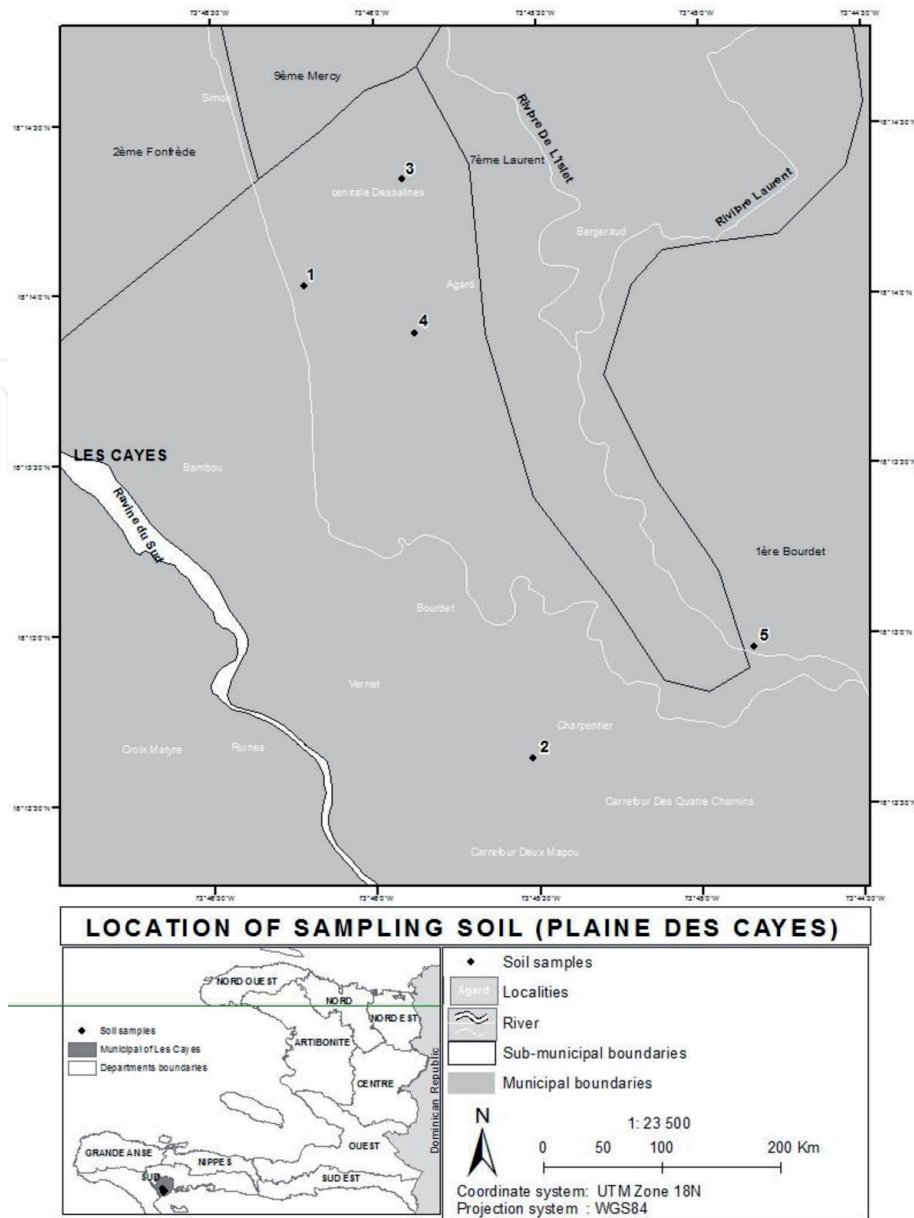


Figure 2.
Location of sampling soil (Plaine des Cayes). Source: [16].

Fraction	Particle size distribution %
Clay (< 2 µm)	25.9
Fine silt (2/20 µm)	25.4
Coarse lime (20/50 µm)	6
Fine sands (50/200 µm)	7.1
Coarse sand (200/2000 µm)	35.6

Table 1.
Particle size distribution of soil elements.

temperature ($23 \pm 2^\circ\text{C}$). At the end of the stirring period, the tubes were placed in an upright position for 20 h. Since soil particles settled much faster than oocysts, due to their different densities, the solution at the top of each tube was removed and

Parameters		Laboratory	Protocol execution
Sedimentometry		National Laboratory of Building and Public Works - LNBTP	NF X 31-107
Size			NF X 31-107
Water content			NF ISO 11465
Soil pH	Water-pH	National Institute of Agronomic Research – INRA	NF ISO 10390
	KCl-pH		
Carbonate content	Total limestone		NF ISO 10693
	Active limestone		NF X 31-106
Organic carbon content			NF ISO 10694
Clay content			NF X 31-107
CEC			NF X 31-130
Specific soil surface		Institute for Radiological Protection and Nuclear Safety - IRSN	NF ISO 9277

Table 2.
Physicochemical analysis of soil.

analyzed for oocyst amounts. The solution was analyzed by epifluorescence, and the determination of the amount of oocysts retained in the soil (q_e) was calculated using Eq. (5):

$$q_e = (C_0 - C_e) * V/m \quad (5)$$

where q_e is the amount of oocysts absorbed per unit mass of solid expressed in L/g particles; C_0 , the initial concentration of suspension oocysts/L; C_e , the concentration of colloidal particles balanced oocysts/L; V , the volume of solution used in L; and m , the mass in grams of dry soil.

4.5 Enumeration of *C. parvum* oocysts

Enumeration of *Cryptosporidium* oocysts was conducted by the method of concentration and counting [70]. Oocyst concentration in the suspension was determined by monoclonal antibodies' staining and epifluorescence. Each final suspension tube containing oocysts was placed in an Eppendorf standard micro test tube (2 ml volume). To this suspension, a volume of 250 μ l fluorescein isothiocyanate (FITC)-conjugated monoclonal antibody was added, and the mixture was incubated for 30 min at 36°C. Following incubation, the stained sample was subjected to three rinses with phosphate buffered saline (pH 7.0, 0.1 mM) and centrifugally washed (4000 \times g) for removal of unattached antibodies. Then, 100- μ l aliquots were placed on six-well chamber slides and fixed with 100% methanol.

5. Retention of *C. parvum* oocysts in the soil

Tables 2 and 3 present the results of physicochemical analysis and particle size distribution of the soil of the study. These analyses indicate that the soil is characterized by fine particles; the size of the largest element is 2.50 mm.

Soil type	texture	% of soil			pH	% organic carbon	CEC (cmol/kg) ^a	Specific surface
		sand	silt	clay				
Alluvial soil	Clay loams	42.7	31.4	25.9	8.52	10.3	15.2	16.32

^a CEC, cation exchange capacity (units of charge per weight of soil)

Table 3.
Soil characterization data used in this study.

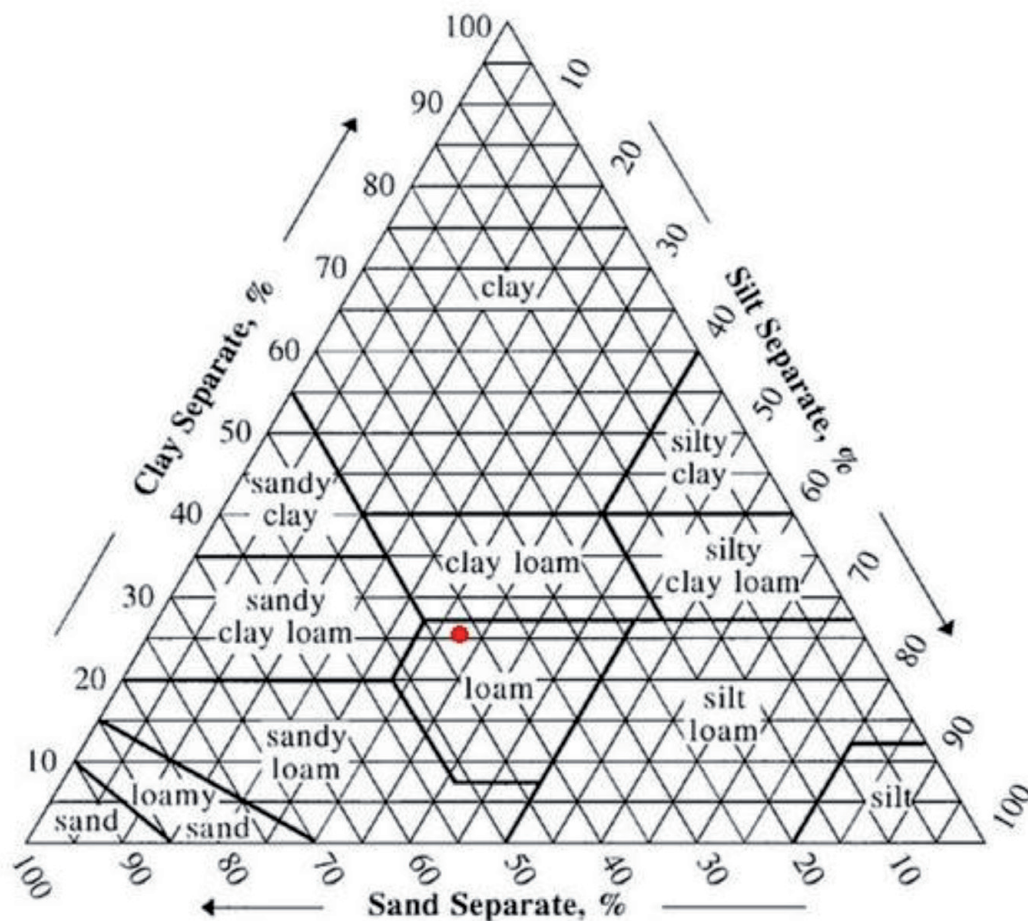


Figure 3.
Particle size distribution of the soil sample of the study. Source: [16].

This fraction represents about 25% of the sample (**Figure 3**) and consisted of 35.6% coarse sand, 7.1% fine sands, 25.4% fine silt, 6% coarse silt, and 25.9% clay. According to [71] the largest CEC values were observed for the particle size analysis 15.2 (cmol/kg) of cation exchange capacity (CEC) and a large surface area due to the presence of silts and clays there for a large number of binding sites. The highest pH value was observed pH (8.52) probably due to the high calcium carbonate content (10.3 g/kg) and a high total calcium concentration (590 g/kg).

The retention of *C. parvum* oocysts in soil was investigated in a series of batch equilibrium experiments. When combined with soil particles, and in presence of CaCl_2 solution, the oocysts were removed from the suspension with a high rate (**Table 4**). The results summarized in **Table 5** showed that oocysts, in the solution of NaBr, were transferred to the solid phase, suggesting a chemical environment favorable for the retention of oocysts. In addition the alkaline pH measured in the physicochemical

Samples	C ₀ (oocysts)	C _e (oocyst/L)	V _{CaCl₂}	Msol(g)	q _e (oocyst.L/g)
Cc1	1ml contains 40.000	0	39	4	400
Cc2	2ml contains 80.000	0	38	4	800
Cc3	3ml contains 120.000	0	37	4	1200
Cc4	4ml contains 160.000	0	36	4	1600
Cc5	5ml contains 200.000	13	35	4	2000
Cc6	6ml contains 240.000	13	34	4	2400

Table 4.
 Results of the test absorption studies between oocysts and soil with CaCl₂.

Sample	C ₀ (oocysts)	C _e (oocyst/L)	V _{NaBr}	Msol(g)	q _e (oocyst.L/g)
Cc1	1ml contains 40.000	0	39	4	400
Cc2	2ml contains 80.000	0	38	4	800
Cc3	3ml contains 120.000	0	37	4	1200
Cc4	4ml contains 160.000	0	36	4	1600
Cc5	5ml contains 200.000	0	35	4	2000
Cc6	6ml contains 240.000	0	34	4	2400

Table 5.
 Results of the test absorption studies between oocysts and soil with NaBr.

analyses of the soil can increase the negative charge of zeta potential of oocysts and ultimately reduce the retention capacity of the soil. This could explain the presence of oocysts in groundwater. However, interactions between small colloid particles, the size of *C. parvum* oocysts, and small soil particles, typically the clay-sized fraction (<2 μm), depend to a large extent on electrostatic and other surface forces. Hence, surface charge, characterized as electrophoretic mobility or zeta potential, may govern the interaction between oocysts and soil particles [72]. Furthermore keeping the soil in its natural condition including clay particles and organic matter, which are important for adhesion and may be high in water suspensions in the environment. The association of oocysts with clay minerals has been attributed to high cation exchange capacity (CEC) of clays [72]. This could explain adsorption of oocysts on soil particles in the test batch. The high content of organic material obtained may affect the transport of pathogenic microorganisms in the soil to promote their retention [73]. Tufenkji et al. found that the oocyst removal efficiency depended on ionic strength and solution pH.

Other studies have reported that the ionic strength of the solution can influence the behavior of oocysts in the soil. Increasing the ionic strength of the water can alter the hydrophobic behavior of oocysts. According to the Debye-Hückel equation, the two solutions used for this study had different ionic strength. This distribution can be explained by the retention of oocysts in the solution containing CaCl₂ (**Table 4**). While for NaBr, for the same ionic strength, the activity of Na⁺ ions is almost identical to the activity of Br⁻ ions. There is a total transfer of the oocysts of the aqueous phase to the solid phase (**Table 5**). Indeed, changes in particle surface chemistry can have a significant influence on particle aggregation and adhesion [62, 74]. An improved understanding of the influence of oocyst purification and handling methods on oocyst surface chemistry and subsequent stability (vide infra) in water may lead to more effective oocyst removal in engineered processes [75]. Thomas et al. [76] recently reported that oocysts suspended in CaCl₂ solutions had near-zero electrophoretic mobility. Brush et al. [62] have reported that variations in observed electrophoretic mobilities were caused by dissimilarities in purification techniques.

5.1 Dynamics of pollution of water resources in the city of Les Cayes

Pollution dynamics of water resources refer in this chapter to all mechanisms resulting from anthropogenic activities that contribute to the degradation of water quality. This dynamic is the result of a series of actions to be closely linked to spatial development, population growth, and especially to inaction of the public authorities.

The groundwater of the Plaine des Cayes is an important resource. From an ecological point of view, they represent a quantitatively large water reserve and contribute to the feeding of many lakes and rivers. In addition, they provide a significant part of the water supply for the population. The mode of supply is made from groundwater withdrawals with the installation of wells and boreholes and by capture of sources. Distribution takes place from networks, private connections, and public fountains. According to the data of the information, the water of the municipal system is fed by two boreholes with a flow of 66 l/s and an average production of the order of 10,134 m³/day.

Work carried out on the groundwaters of the country indicates their saline contamination [77] and the presence of pathogenic microorganisms (S/Committee on drinking water and human waste disposal, 1991) [78] and chemical pollutants [79]. In Haiti, several factors include the lack of a system for the collection and drainage of urban effluents, the absence of wastewater treatment plants, the discharge of septic tank effluents into karstic and alluvial formations, as well as the construction of latrines in the aforementioned geological formations, contribute to microbiological contamination of groundwater. A total of 110 fecal coliforms per 100 ml of water was detected in the water distributed by the public service of the city of Les Cayes (S/Committee on drinking water and human waste disposal, 1991).

Based on findings, it appears that the population of the city of Les Cayes resorts to the use of nonreturn latrines and WC with septic tanks, improved latrines, and with non-defined systems (defecation in open air) for the evacuation of their excreta. In the same manner, the people of Les Cayes use various channels for the evacuation of their solid waste: direct removal by the trucks and other discharges into waterways, wastelands, drains, etc. Quite often, the waste which undergoes putrefaction on garbage heaps as well as it does in trash bins produces an extremely toxic liquid called lixiviant. This situation can contribute to the contamination of the water table's water resources through human fecal matter.

All of these pose serious threats to water resources that are heavily exploited in the area through wells, springs, and boreholes. Groundwater is generally polluted by the excreta. People are digging latrines until they reach the surface of the water table. After a rise of a water table above the ground surface, the excreta can be mobilized by the runoff and can be dispersed all over the surface and can pose a significant pollution hazard. It is clear that solid waste and wastewater have as receptacle the aquatic ecosystems and greatly contribute to altering the quality of water resources.

5.1.1 Health impact related to the degradation of water resources

Regarding cryptosporidiosis in Haiti, in the early 2000s, a series of environmental investigations had been conducted in Port-au-Prince and its surroundings, Les Cayes, and Cap-Haitien to identify human contamination sources. So far, these surveys consisted only in detecting *Cryptosporidium* oocysts in the environment by screening different types of water (surface water, groundwater, public water supplies) used by the population [10–12]. Cryptosporidiosis is one of the most frequent

causes of diarrhea in Haiti. Transmission in young children, HIV-infected individuals, and people living in low socioeconomic conditions is probably due to consumption of water or food contaminated by *Cryptosporidium* oocysts. In tropical areas and under unfavorable socioeconomic conditions, cryptosporidiosis of the child is associated with a risk of prolonged diarrhea, malnutrition, and possibly psychomotor retardation and lectin-related mannose deficiency [80]. Cryptosporidiosis is responsible for 17.5% of acute diarrhea cases in children <2 years old [81] and for 30% of HIV patients with chronic diarrhea [82]. Cryptosporidiosis is associated with Haitian children with malnutrition and lectin-related mannose deficiency. In a study conducted in Port-au-Prince, the presence of *Cryptosporidium* oocysts was shown in 158 people (a prevalence of 10.3%). Among these individuals, 56 out of 57 (98%) adults and 7 out of 36 (19%) children were HIV⁺. Genotyping identified three species: 59% *C. hominis*, 38% *C. parvum*, and 3% *C. felis* [12]. It is one of the leading causes of morbidity and mortality in people with AIDS [82]. Cryptosporidiosis is considered as a significant health problem in Haiti where cryptosporidiosis appears to be closely related to environmental issues. Water and sanitation are environmental issues to their very core and together constitute one of the top drivers of development. Water and sanitation provision have an impact on the health of the environment, through downstream pollution in particular.

5.1.2 Environmental impacts related to the degradation of water resources

Pollution of water resources has a particular impact on the environment, especially since water is an essential component of the ecosystem. Water pollution affects air, soil, and plants. In this, the stagnation of wastewater in the open spaces generates foul odors which constitute an inconvenience for the population. This mode of management or disposal of wastewater causes inter alia disturbances in the nutrient cycle, changes in the structure and functioning of the biotic community, and a biological imbalance in aquatic ecosystems. The high pollutant loads contained in water surface are at the origin of eutrophication. In addition, the weakness of the collection system means that solid waste is dispersed in gullies in public squares, in public markets, and accumulates in open drainage channels contributing to the degradation of the environment. In addition, the accumulation of organic waste in the urban environment favors murine swarming, a reservoir of *Cryptosporidium muris*, a species recently found in humans in Peru [83]. Leachate from leachate is leaking into the drinking water system, with old and poorly maintained pipelines on the surface in many streets. These conditions of urban insalubrity explain the particularly high rate of contamination by *Cryptosporidium* oocysts of water for human consumption. The impact on the environment affects the attractiveness of the city of Les Cayes.

6. Conclusion

Pollution of water resources in developing countries is a public health problem. This problem affects everyday life and the living standards of urban populations. In the urban areas of poor countries, uncontrolled population growth puts severe pressure on existing natural resources, particularly water resources, resulting in accelerated environmental degradation. In particular, the water resources of the city of Les Cayes are subject to various pressures on a daily basis as a result of poor sanitation and poor solid waste management. To understand the dynamics of water resource pollution by microorganisms, a study on the behavior of *Cryptosporidium* oocysts under chemical conditions was carried out. The objective of this study was to investigate the behavior of *Cryptosporidium* oocysts under chemical conditions

and soil characteristics in saturated porous media and to describe also the water pollution dynamics of *Cryptosporidium* oocysts. Batch equilibrium tests were used to describe the partitioning of *Cryptosporidium* particles between solid and liquid phases and play a significant role in the oocyst removal from the pore fluid. Therefore it is necessary to reduce the level of exposure of the population of Les Cayes through the construction of livestock farms to prevent the free movement of animals in the city, the elimination of wild dumps, and the treatment of urban effluents, latrine sludge, and septic tanks. It is important to regularly monitor water quality (monitoring) and evaluate progress. Good management of water resources on our study site requires close collaboration between research institutes, water companies, and health authorities.

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