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Chemical Pollution of Drinking Water in Haiti: An Important Threat to Public Health

Alexandra Emmanuel and Evens Emmanuel

Abstract

The geophysical environment of the Republic of Haiti is characterized by hydrological and biogeographical climatic phenomena, and a relief marked by its rugged appearance. Most of the territory is occupied by mountains formed of limestone. The differences in level are very marked. Fragmentation is another feature of the relief. These environmental imperfections juxtaposed with difficult socioeconomic conditions and anthropogenic actions raise questions about possible chemical metal pollution of the country's water resources. Indeed, the predominance of limestone in the Haitian geology generate water hardness, and in the case where the magnesium concentration is less than 7 mg/l, this water may be the source of cardiovascular diseases. Studies carried out on several water points show a total hardness greater than 200 mg/l. In Port-au-Prince, concentrations of lead ranging from 40 µg/L to 90 µg/L and high Cr (III) risks were measured and estimated in groundwater and drinking water. Concentration of fluorine ranging from 0 to 2 mg/l were obtained from water resources. Concentration above 1.5 mg/l have been found from alluvial aquifers. Chronic public health risks, such as cardiovascular diseases, deterioration of the psychological development of children, irreversible functional and morphological renal changes, and dental fluorosis, strain Haiti's water resources. Chemicals' exposures seem to pose a threat to public health in Haiti, which need to be studied. The aim of this study is: (i) to analyze the contribution of geology and anthropogenic actions in the alteration of water quality, (ii) to review the toxicology of chemicals detected in water distributed in Port-au-Prince.

Keywords: chemical pollutions, drinking water, environmental health, medical geology, One Health, Haiti

1. Introduction

Water is essential for sustaining life, yet it is also the source of many diseases for living things [1]. With the increase in population and the development of industrial activities, surface water resources and groundwater have become increasingly polluted. Thus, humans are exposed to many chemicals found in drinking water.

Several chemicals (organic and inorganic) have been identified in drinking water, and the sources of pollution of the drinking water system are multiple [2]. Among these pollutants, the literature reports particularly chlorine disinfection by-

products [3–5], fluorine [6–8], lead [9, 10] chromium [11–13], cadmium [14, 15], nitrates [16, 17], pesticides [18, 19], hardness [20, 21], arsenic [22, 23], etc. The presence of chemical substances in the municipal drinking water is a major health concern. Indeed, some substances detected in drinking water have been the subject of epidemiological studies [1]. The health effects reported in the literature are different cases of cancer, reproductive problems (malformations) cardiovascular and neurological diseases. Drinking water is therefore an important route of exposure to chemicals.

Pollutants, particularly heavy metals are released into the environment from a wide spectrum of natural and anthropogenic sources [24]. Heavy metals are omnipresent in the environment, occurring in varying concentrations in air, bedrock, soil, water, and all biological matter [25, 26]. The principal anthropogenic sources are industrial and urban effluents, runoff water, drinking water production and distribution equipment and drinking water treatment processes [1]. The presence of heavy metals in the environment constitutes a potential source of both soil and groundwater pollution.

In Haiti, the work carried out in the field of the physicochemical quality of water intended for pollutants such as: lead, chromium [27], fluorine [28]. Excessive concentrations of hardness have also been observed in water resources [29]. These concentrations of natural origin are added to those generated by anthropogenic actions, such as poor management of solid waste, the absence of urban sanitation networks and water treatment plants only increase the rate of human exposures to these pollutants. These exposures to chemical substances continue to put Haitians at risk, and several examples shed light on the realities of risk management with respect to toxic chemicals in developing Countries [30]. The fact that the hydrographic basin of Port-au-Prince consists mainly of karst aquifers [31], rainwater, polluted by atmospheric particles of substances originating from industrial activities, and urban wastewater feeds, through the dominant geology, groundwater, thus leading to suppose that the water resources of this region are subject to significant chemical pollution.

The impact on human health of natural materials such as water, rocks and minerals has been known for thousands of years, but there have been few systematic and multidisciplinary studies on the relationship between geologic materials and processes and human health (the field of study commonly referred to as medical geology) [32]. In order to achieve a better understanding in urban and rural areas of Haiti of the different routes of exposure and the causes of a number of environmental health problems generated by exposure to high concentrations of essential and non-essential chemicals for the organism that are detected in drinking water, it seems relevant that geoscientists, environmental and health science researchers; as well as public health specialists combine their skills to approach the problem of pollution of water intended for human consumption by taking into account the two main sources of the qualitative degradation of water: “geological contributions and anthropogenic actions”. The aim of this study is: (i) to analyze the contribution of geology and anthropogenic actions in the alteration of water quality, (ii) to review the toxicology of chemicals detected in water distributed in Port-au-Prince.

2. Medical geology and environmental health in the geographical context of Port-au-Prince

2.1 Environmental health and assessment of health risks associated with chemical mixtures in drinking water

During the 1950s, forms of anxiety gradually manifested themselves regarding the state of environmental degradation and its harmful consequences for the

survival of ecosystems and for development [33]. Indeed, since the said decade, the environment-human health relationship has become a major concern in the field of public health. The questions of contaminated soil, emanations from landfills, destruction of the ozone layer, global warming, food contamination, radiation emitted by household appliances, new biological hazards ... are among the subjects of intervention by government authorities [34].

Abenhaim [35] argues “Environmental health issues are among the most complex for scientists to study and the most difficult for policy makers to resolve. First, because it is rare that the exhibitions are pure, thus leaving room for many confounding factors. Then, because the contaminations are generally in relatively small quantity, at the limits of the observable effects. Finally, because the consequences of exposure often occur over the long term” [35]. Exposure to chemical mixtures is a reality that would seem to dictate the need to pay much attention to hazard identification, exposure assessment and risk characterization [36], of mixtures in water intended for human consumption. Contrary to this environmental reality, the toxicological reality is that until recently most of the research carried out in this field has been devoted to studies on the effects of substances acting independently, without considering the interactions or combined effects between pollutants at the inside the human organism [37].

In Haiti, all the work carried out on the health risk linked to the pollution of drinking water by chemical substances, the risk characterization was made based on the independent effects of the pollutants studied. This approach provides information on the level of exposure of the population to a substance but does not make it possible to assess the interactions of the various pollutants detected in the distributed water. It is now widely recognized that studying the combined effects of chemical mixtures in drinking water is an integral part of public health [37]. Characterizing the combined actions of chemical mixtures involves the challenge of how to define the antagonistic, additive, or synergistic effect. It is therefore important to understand the terminology that describes the combined effect of the agents in terms of the mechanism of action. Seventy years ago, three basic concepts of common action or the interaction of the combination of chemicals were defined by biomathematicians [38–40] and they are still valid today.

Indeed, Bliss [38] identified three modes of action of constituents within a mixture vis-à-vis living organisms:

1. “*Independent joint action*”: in this type of action, the constituents act on different sites of action and the biological response of one constituent is not influenced by another.
2. “*Similar joint action*”: the constituents act on the same sites of action and the biological response of one constituent is not influenced by another. This is the approach most used for the study of mixtures.
3. “*Synergistic action*”: where the response of a mixture cannot be known by the isolated responses of the constituents. The response of a mixture depends on the combined effects of its constituents.

All three basic principles of common action of pollutants are theoretical. However, these concepts will most likely need to be addressed at the same time, especially when the mixtures consist of more than two compounds and when the targets (individuals rather than cells) are more complex.

Fox et al. [41] considers the risk assessment of chemical mixtures or the cumulative risk assessment (CRA) as the most recent step in the evolution of assessment.

USEPA [42, 43] defines this approach as an analysis, characterization, and possible quantification of the combined risks to human health or the environment due to multiple substances or stressors. This definition suggests that additivity is the initially accepted mode of action for the implementation of ERC.

U.S. EPA [44] developed for the implementation of cumulative risk assessment, the Hazard Index (HI) method. This approach first assesses the effects of a substance acting independently of the others. HI is calculated by dividing the measured or estimated exposure concentration by the reference concentration (RfC):

$$HI = \text{Measured or estimated exposure concentration} / RfC$$

For $HI < 1$, the exposure concentration is below the cutoff value, so no health effect can be expected. On the other hand, for $HI \geq 1$, the exposure concentration exceeds the threshold value, further research on the health effects of the pollutant is recommended, by calculating the Hazard metric HM.

$$HM = \text{Measured or estimated exposure concentration} / \text{NOAEL or adjusted LOAEL}$$

Based on the additive action of pollutants, the application of the HI or HM model to assess the concentration of exposure due to chemical mixtures can be also expressed:

$$LCE = \frac{C_1}{M_1} + \frac{C_2}{M_2} + \frac{C_n}{M_n} \leq 1 \quad (1)$$

LCE: Limit of exposure concentration

C1, C2 and Cn: observed concentrations.

M: Maximum acceptable concentration (threshold value)

In the distribution units where chlorination is applied to raw water rich in organic matter, a quite common situation or process in Haiti, the populations served are exposed to a certain number of chemical substances (by example Disinfection by-products (DBPs)), very known for their adverse effects on human health, especially the occurrence of cancers [45, 46]. In the absence of national standards for the quality of drinking water, Haiti applies the guidelines of the World Health Organization. The application of the HI or HM model in the evaluation of the combined effects of by-products could be, in a simplified manner, carried out from:

$$THMs = \frac{EcCHBr_3}{TS_{WHO}CHBr_3} + \frac{EcCHBr_2Cl}{TS_{WHO}CHBr_2Cl} + \frac{EcCHBrCl_2}{TS_{WHO}CHBrCl_2} + \frac{EcCHCl_3}{TS_{WHO}CHCl_3} < 1 \quad (2)$$

THMs: Trihalomethanes

EC: Exposure concentration

CHBr₃: Bromoform

CHBr₂Cl: Chlorodibromomethane

CHBrCl₂: Bromodichloromethane

CHCl₃: Chloroform

TSWHO: WHO threshold value Different types of complex mixtures require different approaches, and the usefulness of a certain approach depends on the context in which one is confronted with a mixture, and on the amount, type and quality of the available data on the chemistry and the toxicity of the mixture [47]. Scientific literature reports the occurrence of several detected in drinking water in Haiti [26–29]. Moreover, MSPP and WHO [48] note “the quality of water intended for human consumption is not subject to any control. In such a context, the study of

the combined effects of several chemical substances in drinking water and the assessment of the risks generated for human health constitute an important topic of transdisciplinary public health research.

2.2 Medical geology and ONE HEALTH approach in health risks assessment of drinking water in Haiti

Located between 18° and 20°6' Northern latitude and between 71°20' and 74°30' Western longitude, Haiti divides with Dominican Republic “the island of Hispaniola” which is the second biggest island of the Caribbean. Its capital, Port-au-Prince, is settled at the bottom of the Gulf of “La Gonâve”, in the south border of Plain of Cul-de-sac and in the north catchment area of the “Massif de la Selle” piedmont (Figure 1). The main municipalities which constitute urban community of Port-au-Prince are Port-au-Prince, Delmas, Pétiön-ville, Croix-des-bouquets, Gressier and Carrefour.

Haiti is exposed to a considerable ecological imbalance, characterized by catastrophic flooding associated to torrential rains and hurricanes, devastating earthquakes, and deforestation [50]. Other problems, resulting from this imbalance include land use forming the immediate perimeter of headwaters and wells, wetlands draining, arable soils erosion, the decrease of the headwaters flow and groundwater, seawater intrusion, sewers obstruction and fecal pollution [51]. In addition, Haiti is one of the most vulnerable countries to climate change [52]. In general, Haiti’s geophysical environment is characterized by rugged relief. Most of the territory is occupied by mountains formed of limestone and karst aquifers [31, 53–55]. The existence of karst aquifers conditions in rainy weather the contamination of groundwater by surface pollution. Indeed, the main characteristics of

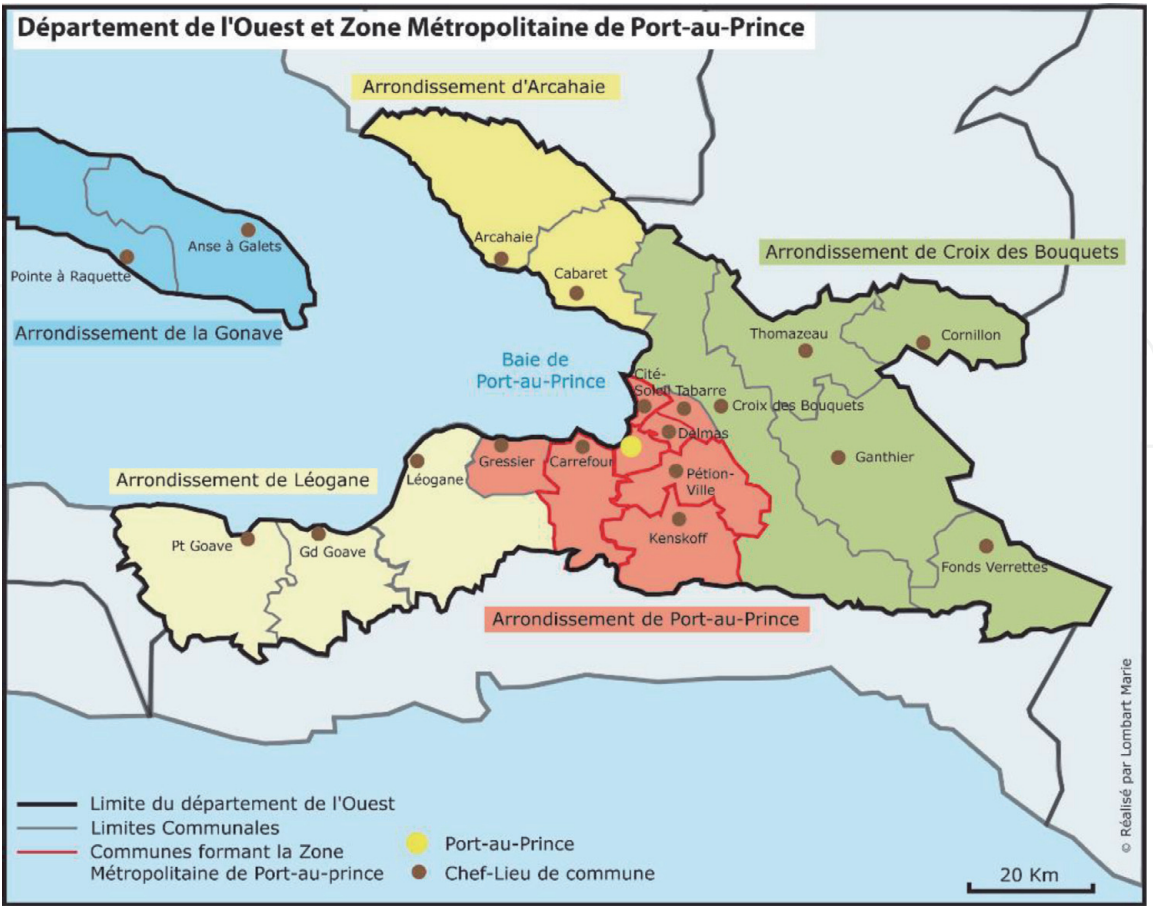


Figure 1.
Map of the west department of Haiti and metropolitan area of Port-au-Prince [49].

karst aquifers are the existence of irregular networks of pores, cracks, fractures and pipes of various shapes and sizes. Such a structure, of significant physical and geometric heterogeneity, causes complex hydraulic conditions and the spatial and temporal variability of hydraulic parameters. After a downpour, rapid and turbulent groundwater recharge occurs through drainage in large conduits with high volume of unfiltered water [56].

Groundwater resources at Port-au-Prince are vulnerable to contamination related to polluted water infiltration such as leachates, cesspools and septic tanks, stormwater runoff, waste oil discharging, over-irrigation and industrial discharging [50]. These sources of groundwater recharge may contain organic and inorganic compounds which can be in dissolved and colloidal forms or associated to particles. Microbiological and physicochemical characterization of groundwater resources in the metropolitan area of Port-au-Prince, among other things, highlight the presence of heavy metals [57], fecal coliforms [27] and *Cryptosporidium* oocysts [58]. In addition to bacterial and metal contaminations, it was found that aquifers in Haiti are also exposed to seawater pollution [50]. According to Gonfiantini and Simonot [59], the salt water is slightly enriched with heavy isotopes with respect to fresh groundwater, not showing any deviation from the straight line of meteoric waters. In the area of Port-au-Prince, the salinity of the groundwater is the result of seawater intrusion because of intensive exploitation [59].

The geophysical environment of Port-au-Prince, the inefficiency of the sanitation system (collection and treatment of solid waste, drainage, and treatment of wastewater, etc.), which contribute to the microbiological and physicochemical quality of the water distributed by public networks to the population gives rise to a particular epidemiological environment where the water generates several dangers for the health of consumers. In such a context, the assessment and management of health risks associated with water intended for human consumption require a multidisciplinary approach and call on researchers, technicians, and specialists in several fields of life and earth sciences as well as the humanities and social sciences.

The 2030 Agenda for Sustainable Development of the United Nations (UN) establishes goals and targets in areas of critical importance for humanity [60, 61], Ramirez-Mendoza et al., 2020 [62]. Indeed, the SDGs are linked to one another, the success of one often depending on the resolution of problems generally associated with another objective [60]. They thus constitute a universal and transversal approach concerning all countries, in the North as in the South. Regarding the issue of water, objective 6 - access to safe water and sanitation - aims to meet the challenges of drinking water, sanitation, and hygiene for populations, as well as issues concerning aquatic ecosystems. In the absence of quality and sustainable water resources and sanitation, progress in several other areas of the Sustainable Development Goals, including health, education and reduce of poverty, will also be delayed [60]. This objective, taken in the prism of the situation of the urban and hydrological context, as well as the geophysical environment of Haiti, raises concerns. However, the launching by public authorities and funding agencies of large research programs with the objective of generating and applying knowledge, promoting innovations in the life and earth sciences, as well as in human and social sciences, in a context of transdisciplinary would be of great use, even essential for the development to achieve the various objectives [63]. Indeed, Medical geology, the science that deals with the relationship between natural geological factors and human and animal health problems [32], and the One Health approach, an approach that attempts to bringing together medical/public health researchers, veterinary researchers, and environmental scientists to tackle health problems, provides an adequate theoretical framework to address environmental health problems resulting from the degradation of natural environment in Port-au- Prince.

The interconnectedness of human, animal, and environmental health is at the heart of One Health, an increasingly important prism through which governments, NGOs (nongovernmental organizations), and practitioners view human health) [64]. Mazet et al., [65] note “An important implication of the One Health approach is that integrated policy interventions that simultaneously and holistically address multiple and interacting causes of poor human health—unsafe and scarce water, lack of sanitation, food insecurity, and proximity between animals and humans—will yield significantly larger health benefits than policies that target each of these factors individually and in isolation. By its very nature, the One Health approach is transdisciplinary, since it is predicated on agricultural scientists, anthropologists, economists, educators, engineers, entomologists, epidemiologists, hydrologists, microbiologists, nutritionists, physicians, public health professionals, sociologists, and veterinarians working collaboratively to improve and promote both human and animal health” [65].

3. Chemistry and toxicology of selected pollutants detected in water distributed in Port-au-Prince

3.1 Presence of fluoride in drinking water and risk for human health

Fluoride, the 13th most abundant element in the earth’s crust, is essential to human life [66]. Elemental fluorine almost never occurs in nature, but fluoride is widely distributed in the Earth’s crust, mainly as the mineral’s fluorspar, cryolite, apatite, mica, hornblende, and fluorite [67, 68]. **Table 1** shows certain physical and chemical properties of fluoride.

Fluoride participates in the formation of bones and teeth and contributes to their solidification. It enters the body in the form of fluorides through drinking water, food, air, drugs, and cosmetics. It is known to have beneficial and harmful effects on humans [69]. Indeed, its deficiency has long been linked to the incidence of dental caries [70], while prolonged excessive intake has been associated with fluorosis [71]. Large populations throughout parts of the developing world suffer the effects of chronic endemic fluorosis [70].

The most important source of fluoride intake in the human body is drinking water [72]. According to WHO [73], the guideline value for fluoride in drinking-water is 1.5 mg/L, based on increasing risk of dental fluorosis at higher

	Fluoride
Molecular formula	F ₂
CAS#	7782-41-4
Molecular Weight	37.996 g/mol
Melting point	−219°C
Boiling Point	−188.13°C
Solubility	Water
Density	1.517 at −188.13°C
Vapor pressure	760 mm Hg at 85 K
Source	https://pubchem.ncbi.nlm.nih.gov/compound/24524

Table 1.
Physical and chemical properties of fluoride.

concentrations and that progressively higher levels lead to increasing risks of skeletal fluorosis. This value is higher than that recommended for artificial fluoridation of water supplies for prevention of dental caries, which is usually 0.5–1.0 mg/L. WHO [74] recommends that, in setting a standard, Member States should consider drinking-water consumption and the intake of fluoride from other sources. Nevertheless, a content of 1 mg/l of fluoride ions is approximately the desirable concentration in the water supplied to the population to ensure optimal dental health [75]. However, several factors, including temperature, can influence this optimum value, which varies from one climatic region to another. It is therefore important to determine this optimal dose for each region depending on whether it is in a temperate zone or in a tropical zone [76]. Dean [77] has shown that the optimum concentration of fluorine as a function of the ambient temperature is 1.0–1.2 mg/l.

The optimal dose of fluoride in drinking water is defined as the amount of fluoride which decreases the prevalence of dental caries with the absence of significant fluorosis [78–80]. Fluorosis is the demineralization of tooth enamel by excessive fluoride ingestion during the years of tooth calcification [81]. This phenomenon, observed in children, can range from mild fluorosis to a severe manifestation. Indeed, Dean [78] observed that 10% of children consuming water containing 1.0 mg/l of fluoride could develop benign fluorosis. It is reported in the literature that children living in the southwestern United States develop severe fluorosis, much more so than those living in the midwestern, while both groups are exposed to the supply systems. Water containing the same concentration of fluorine [82]. Other studies have suggested that the extremely high temperature of the southwest is a major factor contributing to the increase in demand for drinking water and the increase in severe and endemic dental fluorosis [80, 81, 82].

In Haiti, studies carried out on the water resources of the Center-Sud hydro-graphic region of Haiti (**Figure 2**), revealed fluorine concentrations between 0 and

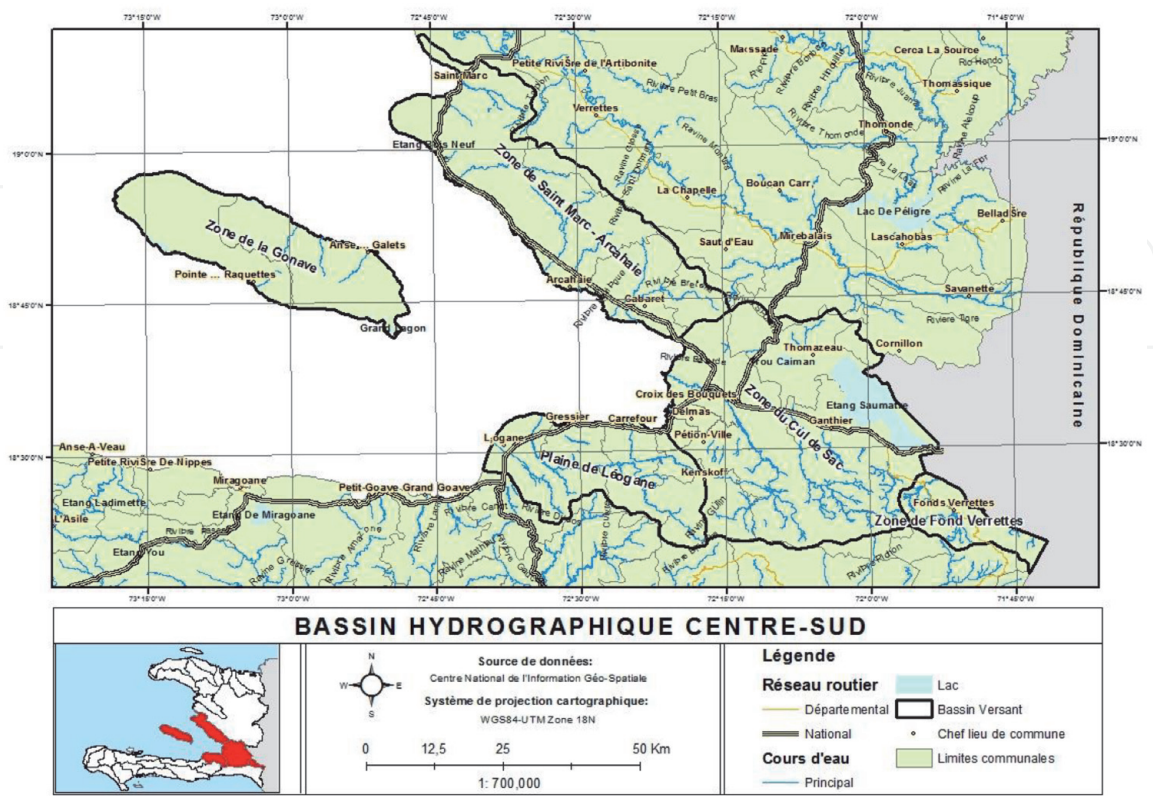


Figure 2.
Map of the “Centre-Sud” hydrographic region of Haiti.

2 mg/l [28, 83]. The various localities of this region are exposed to an average daily temperature ranging from 17 to 36° C.

These observations lead on the one hand to questioning the problems of dental caries and fluorosis from which the populations of the areas studied may suffer and, on the other hand, to determine the optimal dose of fluoride in water intended for human consumption. of the Center-South hydrographic region of the Republic of Haiti. Fluoride’s exposure is a major public health problem particularly for children. Indeed, intake of high-water fluoride concentration during child’s growth and development stages has been associated with mental and physical problems [84–86].

3.2 Water hardness and human health

Hardness is the traditional measure of the capacity of water to react with soap and describes the ability of water to bind soap to form lather, which is a chemical reaction detrimental to the washing process [87]. Water hardness results from the contact of groundwater with rock formations. It is the sum of the concentrations of dissolved polyvalent metal ions which Ca^{2+} and Mg^{2+} are predominant. The sources of the metallic ions are typically sedimentary rocks, and the most common are limestone (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) [66].

Ca and Mg are present as simple ions Ca^{2+} and Mg^{2+} with the Ca levels varying from tens to hundreds of mg/L and the Mg concentrations varying from units of tens of mg/L [88]. Magnesium is significantly less abundant than calcium in rocks and in most natural waters. In addition, magnesium concentrations are much lower in the water than calcium. They are generally less than 50 mg/L, although values higher or equal to 100 mg/L are stored particularly in cold climates [87]. The physical and chemical properties of Ca^{2+} and Mg^{2+} are presented in **Table 2**.

Hardness (in mg equivalent CaCO_3/L) can be determined by substituting the concentration of calcium and magnesium, expressed in mg/L, in the following equation [89]:

$$\text{Total hardness} = 2.497 (\text{Ca}^{2+}, \text{mg/L}) + 4.118 (\text{Mg}^{2+}, \text{mg/L}) \quad (3)$$

Each concentration is multiplied by the ratio of the formula weight of CaCO_3 to the atomic weight of the ion; hence, the factors 2.497 and 4.118 are included in the hardness relation [89].

	Calcium	Magnesium
Molecular formula	Ca^{2+}	Mg
CAS#	7440-70-2	7439-95-4
Molecular Weight	40.08 g/mol	24.305 g/mol
Melting point	842°C	1100°C
Boiling Point	1484°C	651°C
Solubility	Water	Water
Density	1.54g/cm ³	1.738 at 20°C
Vapor pressure	10 mm Hg at 983°C	1 Pa at 428°C
Source	https://pubchem.ncbi.nlm.nih.gov/compound/5460341	https://pubchem.ncbi.nlm.nih.gov/compound/5462224

Table 2.
Physical and chemical properties of Ca^{2+} and Mg^{2+} .

Hardness is most expressed as milligrams of calcium carbonate equivalent per liter [90]. Water containing calcium carbonate at concentrations below 60 mg/l is generally considered as soft; 60–120 mg/l, moderately hard; 120–180 mg/l, hard; and more than 180 mg/l, extremely hard [91]. Although hardness is caused by cations, it may also be discussed in terms of carbonate (temporary) and non-carbonate (permanent) hardness [90].

Calcium and magnesium are essential for the human body [90]. They contribute to the formation and solidification of bones and teeth and play a role in the decrease of neuromuscular excitability, myocardial system, heart, and muscle contractility, intracellular information, transmission, and blood contractility [87, 88, 92]. They also play a major role in the metabolism of almost all cells of the body and interacts with many nutrients [93]. However, inadequate, or excess intake of either nutrient can result in adverse health consequences [90].

According to WHO [90] *“Inadequate intakes of calcium have been associated with increased risks of osteoporosis, nephrolithiasis (kidney stones), colorectal cancer, hypertension and stroke, coronary artery disease, insulin resistance and obesity. Most of these disorders have treatments, but not cures. Owing to a lack of compelling evidence for the role of calcium as a contributory element in relation to these diseases, estimates of calcium requirement have been made based on bone health outcomes, with the goal of optimizing bone mineral density.*

To a great extent, individuals are protected from excess intakes of calcium by a tightly regulated intestinal absorption and elimination mechanism through the action of 1,25-dihydroxyvitamin D, the hormonally active form of vitamin D. When calcium is absorbed more than need, the excess is excreted by the kidney in healthy people who do not have renal impairment” [90].

Magnesium is the fourth most abundant cation in the body and the second most abundant cation in intracellular fluid [90]. In the cardiovascular system, magnesium is the candidate element. It plays an important role as a cofactor and activator of more than 300 enzymatic reactions including glycolysis, ATP metabolism, transport of elements such as Na, K and Ca through membranes, synthesis of proteins and nucleic acids, neuromuscular excitability and muscle contraction [94]. That can have hand in various mechanism where the main is the calcium antagonist effect which can be direct or indirect [95].

Low magnesium levels are associated with endothelial dysfunction, increased vascular reactions, elevated circulating levels of C-reactive protein (a proinflammatory marker that is a risk factor for coronary heart disease) and decreased insulin sensitivity. Low magnesium status has been implicated in hypertension, coronary heart disease, type 2 diabetes mellitus and metabolic syndrome. Magnesium deficiency has been implicated in the pathogenesis of hypertension, with some epidemiological and experimental studies demonstrating a negative correlation between blood pressure and serum magnesium levels. However, data from clinical studies have been less convincing [90].

Indeed, water hardness has become an important public excess health issue [96]. Kobayaski [97] showed a relationship between water hardness and the incidence of vascular diseases. The scientific literature reported the existence of a relationship between cardiovascular disease mortality and water hardness [98–100]. Miyake and Iki [101] observed a lack of association between water hardness and coronary heart diseases mortality in Japan. Nonetheless, many studies covering many countries suggest such a correlation and geochemically it is worthy of serious study [88]. Based on available information in the literature on the association of water hardness and the incidence of cardiovascular diseases (CVD), Eisenberg [102] considered that Mg seems to be the basic element. Indeed, extremely hard natural water with CaCO₃ concentration higher than 200 mg/l with a magnesium concentration

lower than 7 mg/l may affect various organs including the cardiovascular physiology [87].

In Haiti, studies on the spring waters used to supply a part of the population of the Metropolitan Area of Port-au-Prince (MAPP), the most important urban area of the country, showed a total hardness greater than 200 mg/l, with magnesium concentration less than 7 mg/l [29]. In addition, magnesium concentrations ranging from 5.58 to 6.9 mg/l have been measured in groundwater in the metropolitan area of Port-au-Prince [103]. Drinking water low in Mg significantly increases the likelihood of cardiovascular mortality [104]. Catling et al., [105] found significant evidence of an inverse association between magnesium levels in drinking water and cardiovascular mortality following a meta-analysis of case control studies. In Haiti, cardiovascular disease (CVD) is now the leading cause of adult mortality in Haiti [106, 107].

3.3 Groundwater pollution by heavy metals and human health

Metals are natural constituents of the Earth’s crust. The distribution and fate of metals in the environment is governed by their properties and the influence of environmental factors [108]. In environmental compartments, heavy metals constitute an ecological and human health concern since heavy metals are not degraded biologically like certain organic pollutants [109]. Metals exert biological effects that can be beneficial or harmful. Many metals such as Fe, Cu, Co, Mn, Zn, and Cr are essential for humans, and deficiency states with clinical abnormalities have been identified [27, 108, 110]. Other metals such as Hg, Pb, Cd, and As are not known to be essential for any animals [110]. Essential elements can also cause toxic effects at high doses.

In Haiti, heavy metals (lead, chromium, and nickel) have been measured in groundwater [27]. The physical and chemical properties of these heavy metals are presented in **Table 3**.

3.3.1 Effects of chromium on human health

Chromium is one of the heavy metals considered a major pollutant. It has been widely used in industrial processes for leather tanning, dyes and paint preparation,

	Chromium	Lead	Nickel
Molecular formula	Cr	Pb	Ni
CAS#	7440-47-3	7439-92-1	7440-02-0
Molecular Weight	51.996 g/mol	207 g/mol	58.693 g/mol
Melting point	1907°C	327.4°C	1455°C
Boiling Point	2642°C	1740°C	2730°C
Solubility	Water	-	Water
Density	7.14	11.34 g/cm ³	8.9 g/cm ³
Vapor pressure	1 mmHg at 2941° F	1.77 mm Hg at 1000°C	1 mm Hg at 1810°C
Source	https://pubchem.ncbi.nlm.nih.gov/compound/23976	https://pubchem.ncbi.nlm.nih.gov/compound/5352425	https://pubchem.ncbi.nlm.nih.gov/compound/935

Table 3.
Physical and chemical properties of chromium, lead and nickel.

textile manufacturing, paper mills, wood preservation, stainless steel production, and photography [111]. Chromium exists in several oxidation states. The most stable and common forms are trivalent chromium, Cr(III), and hexavalent chromium, Cr(VI), which exhibit contrasting biochemical properties and toxicokinetics [112, 113]. Cr(III) compounds occur naturally in the form of oxides, hydroxides or sulfates, and they are nutritionally necessary to humans for glucose, fat and protein metabolism [114]. In contrast, Cr(VI) compounds are mainly anthropogenic and highly toxic; its mutagenic and carcinogenic nature and high oxidation state enhances its ability to move into living cells [114]. Cr(III) and Cr(VI) interchangeability depends on their concentration in solution, pH, the redox potential (Eh) of the medium, and the presence or absence of a strong oxidant or reductant [111, 115].

The toxicity of chromium is directly dependent on the valence state, with hexavalent chromate Cr(VI) and trivalent chromate Cr(III) being of the greatest interest [112]. Oral bioavailability varies with valence state, with Cr(VI) being more readily absorbed. Cr(VI) can be broken down into Cr(III) within the acidic environment of the stomach [111]. Acute exposure to chromium is indicated by immediate irritation of the eye, nose, throat, and respiratory tract, which results in burning, congestion, epistaxis, and cough. Ulceration, bleeding, and erosion of the nasal septum mark chronic exposure. Cough, chest pain, dyspnea, and chromium-induced asthma indicate exposure to soluble chromium products [113]. If chronic exposure is suspected, in conjunction with weight loss, cough, and hemoptysis, this suggests the development of bronchogenic carcinoma. Dermatological manifestations include painless, slow-healing ulceration of the fingers, knuckles, and forearms. Ingestion is marked by nausea, vomiting, abdominal pain, prostration, and death associated with uremia [114].

3.3.2 Effects of lead on human health

Drinking water is one of the major sources of human exposure to lead [115]. Lead particularly targets the nervous system, blood, and kidney [116]. Many studies found associations between low level environmental Pb exposure and chronic kidney disease, a general term for heterogeneous disorders affecting the structure and function of the kidney (CKD) [117, 118]. Long-term lead exposure may generate irreversible functional and morphological renal changes [119], distal motor neuropathy and possibly seizures and coma [120]. Infants and small children are more sensitive to the effects of lead, which moreover is transported through the placenta to the foetus [121]. Lead accumulation in fetuses and small children might cause developmental disruption in terms of neurological impairment characterized by a decrease of cognitive faculties, which can be reversible or not, evaluated by psychomotor tests such as the verbal IQ (Intellectual Quotient) test [27, 109]. The period when IQ is most affected is from birth to about 4 years of age [122].

Scientific literature on lead water pollution reports “Lead remains a problem in drinking water in many parts of the world, with millions of properties served by distribution systems containing lead components. Strong links have been established between human exposure to lead and health effects in both adults and children. As a result, the allowable levels of lead in drinking water have generally become lower. Implementation of these regulations is difficult with the controls available. Future recommendations for aspiring to zero lead in drinking water are: (i) improving sampling, monitoring and modeling; (ii) Wider application of short-term point-of-use devices; (iii) replacement of all lead pipes and plumbing through applicable regulations and increased awareness public” [123–126].

3.3.3 Effects of nickel on human health

Nickel is insoluble in water. However, when it is in the form of exceptionally fine particles, it ionizes as Ni (II) in water and in body fluids such as blood. During oral exposure, the major effects observed are the death of a child after ingestion of 570 mg of nickel/kg [127] and intestinal disorders such as nausea, abdominal cramps, and diarrhea [128]. Immunological, hematological, hepatic, renal, genotoxic effects on embryonic development and reproduction have been reported depending on the route of entry into the body [129].

4. Conclusion

The aim of this study is: (i) to analyze the contribution of geological factors and anthropogenic actions in the alteration of water quality in Port-au-Prince. The toxicology of chemicals of three heavy metal (chromium, lead, and nickel) and fluoride, substances detected in groundwater and tap water, has been reviewed. The information available on the effects of the selected heavy metals highlights major chemical risks, particularly for children, relating to Pb (II), Cr (III), Cr (VI) and Ni (II) contained in the groundwater were also characterized [27]. The level of pollution of underground water resources in the metropolitan area of Port-au-Prince does not only require the application of an approach based on water treatment processes. It also reflects the need to approach the issue of the quality of water intended for human consumption in this urban space based on a transdisciplinary approach based on the theories of medical geology and the approach. One Health. Indeed, the level of organic and mineral pollution of these resources can compromise the rare efforts made to achieve the SDGs, more particularly the 3, 6, 11, 13. The results available in the literature and used in the context of this work clearly indicate the existence of chronic toxicities of trace heavy metals (Cr, Pb, Ni), fluoride and hardness of drinking water on the human organism and on kidney tissues. In the future, it will be necessary to initiate research work on the combined effects of these substances from observations on laboratory animals and then proceed to modeling to finally arrive at an understanding of certain interactions that may exist between these pollutants.

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