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Review

Morbidity and Water Quality: A Review with a Case Study in Tonosí, Panama

Natasha A. Gómez Zanetti [1], Jorge E. Olmos Guevara [2] and Yazmin L. Mack-Vergara [1,2,3,*]

[1] Centro de Estudios Multidisciplinarios en Ciencias, Ingeniería y Tecnología AIP (CEMCIT AIP), Panama City 0819-07289, Panama
[2] Experimental Center for Engineering, Universidad Tecnológica de Panamá (UTP), Panama City 0819-07289, Panama
[3] Sistema Nacional de Investigación (SNI), Panama City 0816-02852, Panama
* Correspondence: yazmin.mack@utp.ac.pa; Tel.: +507-501-3636

Abstract: Water quality concerns the physical, chemical, and biological factors that could negatively impact human health through its consumption, potentially causing infectious and chronic diseases due to immediate or prolonged exposure. In this context, the objective of this study is to identify diseases that are correlated with the quality of drinking water according to the literature. A systematic review was carried out considering academic and scientific documents from the last 6 years, including peer-reviewed research articles, books, and technical documents, such as standards and regulations related to public health and water quality. Subsequently, these results were applied to a case study from Tonosí (a district in Panama), where a drinking water quality assessment project was developed over the past two years including physicochemical, biological, inorganic chemical, and organic chemical analyses on drinking water during the rainy and dry seasons. Forty-five documents were obtained from the literature review and are presented in tables relating to diseases and water quality parameters. Based on the drinking water quality assessment results from Tonosí, the levels above and below the permissible range—according to the DGNTI-COPANIT 21-2019 Technical Regulation adopted by Panama as a drinking water quality standard—and the diseases associated with the parameters evaluated (in accordance with the literature review) are presented. The results show that there is a possible relationship between some of the water quality parameters and cases of gastrointestinal diseases in the area; however, more in-depth research and statistics at the national level are needed on the health of the population.

Keywords: drinking water quality; morbidity; Tonosí; Panama

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1. Introduction

Morbidity refers to illnesses, diseases, injuries, and disabilities within a population [1]. In addition to monitoring diseases that occur in a region, it is important to know their causes, while data about the frequency and distribution of a disease can help control its spread [1]. Moreover, understanding morbidity in vulnerable regions can contribute to substantial savings in public health systems in developing countries and ensure a better quality of life [2].

Closely connected to public health is water quality, which, according to the World Health Organization (WHO) and other international organizations, can be summarized as the conditions in which water is found with respect to physical, chemical, and biological characteristics, in its natural state or after being altered through human actions [3]. Indeed, deficiencies in water service coverage and quality are typically found among low-income groups, vulnerable populations, and rural communities [4].

Water source contamination involves a variety of hazards, including microbial, chemical, and radiological contaminants [5], and pathogens such as bacteria, viruses, and parasites in drinking water present significant health risks [6]. Likewise, chemical contaminants from industrial, agricultural, and environmental sources can harm human health [7,8], and radiological pollutants also pose a threat [9].

Morbidity is often associated with the quality of water for human consumption [10–12]. Diseases related to water use, including malnutrition, neglected diseases, diarrhea, poisoning, and others, are caused by the presence of microorganisms and chemicals in drinking water [13], and the increased risk of waterborne diseases mainly affects the poorest people. Vulnerability is also high in rural areas where, on the one hand, agriculture and livestock activities in which different chemicals are used are quite common, and, on the other hand, where water quality control is less frequently performed due to the lack of personnel, insufficient equipment, and distance from laboratories.

Many countries do not have specific regulations for controlling the levels of contaminants in drinking water, yet they can adopt the "U.S. Environmental Protection Agency (EPA) standards" [14] and WHO guidelines [15]. The Environmental Protection Agency sets a health-based maximum pollutant level goal, which represents the level at which an adult can regularly consume drinking water throughout his or her lifetime with an adequate margin of safety. However, many pollutants are not specified within the EPA standards [16]. Instead, the World Health Organization publishes guidelines for multiple pollutants, but they are not mandatory, since the WHO is not a regulatory agent [16].

In Panama, the National Institute of Statistics and Census (INEC) gathers population-level morbidity data including incidence, prevalence, and case fatality rates [17]. Specifically, cases of waterborne food diseases such as amoebiasis, diarrhea, giardiasis, food poisoning, salmonellosis, and shigellosis are reported by province. For their part, the Institute of National Aqueducts and Sewers (IDAAN) and the Ministry of Health (MINSA) are responsible for measuring the quality of water sources for human consumption following the DGNTI-COPANIT 21-2019 Technical Regulations for drinking water in Panama [18]. This regulation includes biological parameters (total coliform, *Escherichia coli*, *Giardia* sp., and *Cryptosporidium* sp.), physicochemical parameters (color, turbidity, hydrogen potential, free residual chlorine, and microcystin LR), inorganic chemical parameters (total dissolved solids, nitrate, sulfate, etc.), and organic parameters (trihalomethanes, hydrocarbons, and pesticides).

In Panama, there are different initiatives, strategic plans, regulations, and specific studies that relate certain diseases to certain water quality parameters [19–22]; however, this information is scattered, and there are no studies reporting on the relationship between diseases and drinking water quality parameters. Therefore, the objective of this study is to identify diseases that are correlated with the quality of drinking water, according to the literature, and apply these results to a case study from Tonosí, Panama, where a drinking water quality assessment project was developed over the past two years.

Based on the results of this study and the results from the Tonosí water quality assessment project, it is possible to relate which diseases can occur in the region and propose appropriate actions. In addition, this study serves as a basis for public policy proposals, communication strategies for informing the public, and the implementation of preventive measures not only in Tonosí but also in other regions.

2. Methods

This study consists of a literature review on diseases related to water quality parameters. It is complemented by a case study in the district of Tonosí, in the province of Los Santos, where different water quality parameters have been evaluated through another study. This study aims to answer the following research questions:

1. According to the literature, which diseases are related to water quality parameters?
2. What parameters were measured in Tonosí?
3. Which parameters are beyond the established maximum safety levels?
4. What diseases could the population of Tonosí suffer from according to the literature?

The methodology applied for both the literature review and the case study is detailed below.

2.1. Literature Review

The literature review was carried out considering the period from 2018 to 2024 to include documents from the last 6 years, i.e., the most recent references. Science Direct and PubMed were used to search for academic/scientific literature [23]. Review articles, research articles, and books were included, while a Google search of technical documents was also conducted, including regulations related to public health and water quality.

Below are the combinations of keywords used in the general literature search.

- Morbidity;
- Diseases;
- Waterborne/water-borne diseases;
- Water, sanitation, and hygiene (WASH)-related diseases;
- Quality of water for human consumption;
- Waterborne disease;
- Diseases related to heavy metals in drinking water;
- Diseases related to organic pollutants in drinking water;
- Diseases related to microbial pathogens in drinking water;
- Protozoa;
- Bacteria;
- Viruses;
- Algae;
- Parasitic worms.
- Latin America;
- Panama;
- Tropical climate.

A specific search for diseases related to water quality parameters was carried out according to the DGNTI-COPANIT 21-2019 Technical Regulation for drinking water in Panama [18]:

- Amebiasis;
- Diarrhea;
- Giardiasis;
- Food poisoning;
- Salmonellosis;
- Shigellosis.

Likewise, a search was carried out for water quality parameters related to hydroalimentary diseases reported by the National Institute of Statistics and Census (INEC) [17]:

- Biological parameters;
- Total coliform;
- *Escherichia coli;*
- *Giardia* sp.;
- *Cryptosporidium* sp.
- Physicochemical parameters;
    - Color;
    - Turbidity;
    - Hydrogen potential;
    - Free residual chlorine;
    - Microcystin-LR.
- Inorganic chemical parameters;
    - Total dissolved solids;
    - Nitrate;
    - Sulfate.
- Organic parameters;

- ◦ Trihalomethanes;
- ◦ Hydrocarbons;
- ◦ Pesticides.

Not included are waterborne diseases resulting from recreational water use or other water uses that do not specifically relate to human consumption. Consideration is given to the health conditions found in Panama.

The results are presented in the tables of the Section 3.1 in which diseases are used as column titles and parameters are used as row titles. In cases where an association was found between a disease and a water quality parameter according to the literature, the reference(s) are placed at the intersection of the table. The diseases are grouped by type, just as the water quality parameters are grouped according to the DGNTI-COPANIT 21-2019 Technical Regulations for drinking water in Panama.

2.2. Case Study

The case study is carried out in the district of Tonosí, province of Los Santos (Figure 1) due to the evident concern of the population about cases of diseases in the area and that in many cases the community relates it to the quality of drinking water. In Panama, there is a high perception of challenges regarding water quality even at a urban level [24].

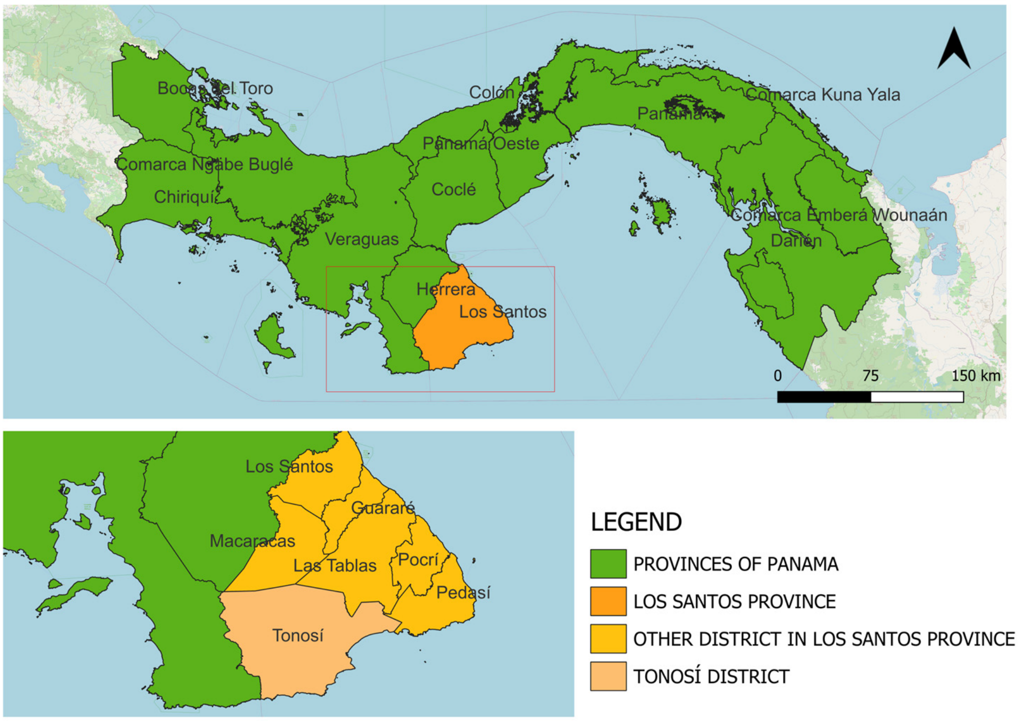

Figure 1. The district of Tonosí is located in the Los Santos province of the Republic of Panama.

To carry out this study, twenty-one sampling points were identified, including the communities of Bebedero, Altos de Güera, El Cortezo, El Cacao, Flores, Cambutal, Guánico, Cañas, and Tonosí (Figure 2), to cover most areas of the district. Four sampling tours were performed, two in the rainy season (October 2022 and December 2023), and two in the dry season (January 2023 and March 2023).

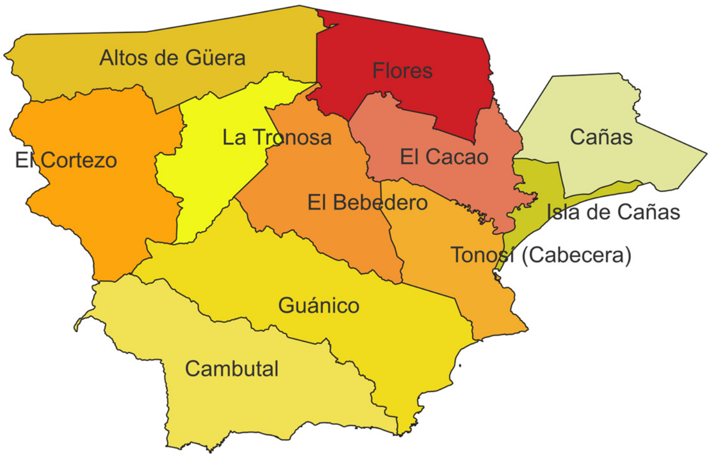

Figure 2. The district of Tonosí is divided into eleven townships: Altos de Güera, Cambutal, Cañas, El Bebedero, El Cacao, El Cortezo, Flores, Guánico, Isla de Cañas, La Tronosa, and Tonosí.

During the tours, the "Standard Methods for the Examination of Water and Wastewater" were adopted and followed step by step. The physicochemical conditions of the water were measured, and samples were taken for specific parameters as a control method for the accuracy of the analyses. Fecal coliforms were analyzed through the membrane filter method. Inorganic chemical parameters such as nitrate, nitrite, sulfates, chlorides, and hardness, were measured through spectrophotometry and volumetric analysis. Elements and heavy metals were analyzed using the total reflection X-ray fluorescence (TXRF) method. Finally, organic compounds from plant protection products and hydrocarbons were detected through gas chromatography and mass spectrometry (GC-MS).

Based on the results obtained in the tours, the parameters that were found outside the values allowed according to the DGNTI-COPANIT Technical Regulation 21-2019 for the assurance of drinking water in Panama were selected. These parameters were compared with the tables representing diseases vs. water quality parameters (Tables 1–10), where the diseases that potentially have an impact on the region were identified (Table 11). Also, from the results obtained, values that were outside the limit established by the World Health Organization for human health were selected and compared with the tables representing diseases vs. water quality parameters, where the diseases that potentially have an impact in the region were identified (Table 12).

The case study focuses on exposing the water quality parameters found in rainy and dry seasons, that exceed the levels allowed by Panamanian and international regulations and making a comparison with the parameters found in the literature and their associated diseases, based on studies from different countries that present similar cases.

3. Results

3.1. Literature Review

The literature review was carried out using the Science Direct and PubMed databases, including the keywords defined in Section 2.1. Out of the 97 articles found, 45 articles in English and with full-text availability covering the last 6 years (from 2018 to 2024) were included in this study. The scope of this study includes waterborne diseases related to water used in human consumption, which have been found in Panama. The incidence of the diseases in Panama included here has been verified through published studies, data from the National Institute of Statistics and Census (INEC), the Institute of National Aqueducts and Sewers (IDAAN), the Ministry of Health (MINSA), and Panamanian newsletters.

Tables 1 and 2 provide the results of biological parameters of water quality for human consumption related to different diseases.

Table 1. Biological parameters related to neurological, nephro-urology, and gastrointestinal factors.

	Neurological	Nephro-Urology	Gastrointestinal				
Parameter/ Diseases	**Neurological Symptoms Nervous System Problems**	**Urinary tract Disease**	**Gastrointestinal Illness**	**Diarrhea**	**Vomiting**	**Abdominal Cramps**	**Nausea**
Cryptosporidium			[14]	[14,25]	[14,25]	[14,25]	[25]
Giardia lamblia			[14]	[14,26]	[14]	[14]	
E. coli		[27,28]		[15,26,28–39]	[28,32,33,38,39]	[15,26–28]	
V. cholerae				[15,26,32,33,35,36]	[26,32,33]	[14,15,34]	
Salmonella spp.				[14,26,33,35,38]	[14,33]	[14,26,34,38]	
Shigella spp.	[26]			[14,26,27,33,35,38]	[14,26,33,38,40]	[14,27,38]	
Viruses (enteric)	[32]		[14,26,41]	[14,26]	[14,26]	[14,26]	

Table 2. Biological parameters related to hepatic, dermatological, immunological, pneumological, and ophthalmological factors.

	Hepatology	Dermatology	Immunology	Pneumology	Ophthalmology
Parameter/ Diseases	**Liver Diseases**	**Skin Diseases**	**Fever**	**Lung Diseases**	**Eye Problems**
Cryptosporidium			[25]		
E. coli	[28]	[33]	[26,28]		
Salmonella spp.			[26]		
Viruses (enteric)				[26,41]	[26,41]

Biological parameters (bacteria, viruses, and parasites) are the most studied in relation to drinking water due to population growth and the lack of drinking water treatment, causing gastrointestinal diseases. Water quality can vary rapidly over time, especially in the rainy season; increased levels of microbial contamination are seen in water sources, and waterborne outbreaks often occur after rains [15]. One of the effects most closely associated with drinking water is diarrhea, which is the world's third leading cause of death among children under five years of age [32].

Table 3 provides the results of physicochemical parameters of water quality for human consumption related to different diseases.

Table 3. Physicochemical parameters related to gastrointestinal diseases.

Parameter/ Diseases	Gastrointestinal				
	Gastrointestinal Illness	Diarrhea	Vomiting	Abdominal Cramps	Nausea
Turbidity	[14]	[14]	[14]	[14]	[14]

Turbidity describes the cloudiness of water caused by suspended particles (e.g., clay and silts), chemical precipitates (e.g., manganese and iron), organic particles (e.g., plant debris), and organisms [15].

Turbidity and gastrointestinal illness are closely connected, as high turbidity levels in water often signal the presence of harmful pathogens such as bacteria, viruses, and parasites. These contaminants can cause gastrointestinal diseases, leading to diarrhea, nausea, and vomiting when consumed [42].

Tables 4–6 provide the results of inorganic chemical parameters of water quality for human consumption related to different diseases.

Table 4. Inorganic chemical parameters related to cardiovascular and endocrine diseases.

Parameter/ Diseases	Cardiovascular					Endocrinology					
	Cardiovascular/ Circulatory System	Increase in Blood Pressure	Hypercholesterolemia	Infantile Methemoglobinemia	Arteriosclerosis	Hypoglycemia	Thyroid Problems	Hair or Fingernail Loss	Reproductive Problems	Pancreatic Diseases	Diabetes
Antimony			[14]			[14]					
Barium	[43]	[14]									
Cyanide (as free cyanide)							[14]				
Lead	[16,44,45]	[14]									
Selenium	[14]							[14]			
Thallium								[14]			
Nitrate				[14,27,46]							
Sodium		[27,47]									
Calcium	[47]										
Potassium	[27]										
Arsenic	[14,16,44, 47,48]								[47]		[16,47,48]
Cadmium									[44]		
Iron	[27,44]										[27,44]
Nickel	[44]										
Zinc	[44]				[44]				[45]	[44]	

Table 5. Inorganic chemical parameters related to neurological, renal, gastrointestinal, and hematological diseases.

	Neurological		Renal		Gastrointestinal								Hematology	
Parameter/ Diseases	**Deficits in Children's Learning**	**Neurological Symptoms Nervous System Problems**	**Kidney Dysfunction Problems**	**Urinary Tract disease**	**Gastrointestinal Illness**	**Diarrhea**	**Vomiting**	**Abdominal Cramps**	**Nausea**	**Stomach Problems**	**Benign Intestinal Polyps**	**Complications with Wilson's Disease**	**Anemia**	**Blood Problems Changes in Blood**
Chlorite		[14]											[14]	
Chlorine (as Cl_2)										[14]				
Chlorine dioxide (as ClO_2)		[14]											[14]	
Asbestos (fiber > 10 µm)											[14]			
Beryllium					[14]									
Cadmium			[14]											
Copper			[14,48]		[14]	[48]	[48]	[48]	[48]	[48]		[14]	[27]	
Cyanide (as free cyanide)		[14]												
Lead	[14,45, 48]	[16,43, 44,48]	[14,16,43,44, 48]					[48]					[16,48]	
Mercury	[48]	[48]	[14,48]			[45,48]	[48]							
Thallium			[14]		[14]									[14]
Sulfate						[27,47]								
Calcium			[47]	[27,47]										
Potassium		[47]			[47]									
Magnesium						[47]								
Arsenic		[47,48]	[16]			[44]	[44,48]	[44]					[27]	
Cadmium			[14,27,44, 48]			[48,49]	[48,49]	[49]						
Manganese	[50,51]	[27,44, 48,52]												
Iron			[47]					[44]					[27]	
Chromium (VI)		[48]	[48]					[44,48]					[27]	
Zinc		[27,44, 45]				[27,44]	[27,44]	[44]					[27]	
Cobalt						[48]	[48]							
Aluminum		[43]												
Barium		[43]		[43]										
Selenium			[48]				[48]							
Fluoride		[53]												

Table 6. Inorganic chemical parameters related to hepatic, dermatological, rheumatic, immunological, pneumological, allergy-related, oncological, and ophthalmological diseases.

	Hepatology		Dermatology	Rheumatology		Immunology		Pneumology		Allergology	Oncology	Ophthalmology
Parameter/ Diseases	**Liver Problems**	**Liver Diseases**	**Skin Diseases**	**Numbness in Fingers or Toes**	**Bone Disease**	**Immune Deficiencies**	**Contamination by Nitrites**	**Lung Diseases**	**Nose irritation**	**Allergic Dermatitis**	**Cancer Risk**	**Eye Problems**
Bromate											[14]	
Chlorine (as Cl_2)									[14]			[14]
Copper		[14,48]									[45]	
Fluoride					[14]							
Nitrate											[27,46,54,55]	
Nitrite							[14]					
Selenium		[48]		[14]								
Thallium		[14]										
Arsenic		[47]	[14]			[16]		[16,47,48]			[16,27,45,47–49,56]	[14]
Cadmium		[43]			[27,44,48]						[44,45,48]	
Iron		[44]						[27]			[44,47]	
Chromium (VI)		[43,48]	[43,44]			[43]		[43,44,48]	[27]	[14]	[27]	
Nickel								[27]			[27,44,48]	
Lead				[48]		[16]				[48]		
Mercury											[48]	
Cobalt								[48]			[48]	

Some of the inorganic chemical parameters mentioned are essential nutrients that are required for various physiological and biochemical functions in the body and can lead to diseases or deficiency syndromes if not found in adequate amounts [57]. For example, an iron-deficient person may have symptoms like weakness, dizziness, headaches, shortness of breath, pale skin, and chest pain; a manganese deficiency can cause serious health problems including weak bones (osteoporosis), muscle and joint pain, and sexual dysfunction; and selenium deficiency has been linked to different cardiovascular diseases [58]. Also, chromium occurs in nature mainly in two oxidation states, Cr (III) and Cr (VI), which have contrasting effects on the human body [27,59]. Chromium (III) itself is not toxic, chromium-based deficiency includes symptoms like irregular blood glucose, fatigue, high cholesterol, and anxiety [44].

On the other hand, zinc maintains the healthy growth of the human body, especially for the growth and development of infants and toddlers. Zinc deficiency can lead to fertility issues, increase the risk of diabetes, and development of cardiovascular diseases [27,60]. Sodium is one of the main constituents of human blood plasma and potassium helps lower blood pressure and also reduces cardiovascular disease [27].

Calcium and magnesium are constituents of bones and teeth. Calcium deficiency causes blood pressure disease (hypertension), bone breakage (osteoporosis), and osteomalacia; and magnesium deficiency can also cause different diseases such as heart arrhythmia, hypertension, and vasoconstriction eclampsia disease generally seen in pregnant women, disease of atherosclerotic, type II mellitus diabetes and bones breakage such as osteoporosis disease is due to the lack of magnesium [43].

Essential trace elements are required by human health in amounts ranging from 50 micrograms to 18 milligrams per day. Acting as catalytic or structural components of larger molecules, they have specific functions and are indispensable for life [61]. Yet in high value and consumed through drinking water, they contribute to the development of other diseases, which are highlighted in this study.

Elements such as sodium (Na^{+}) are associated with an increase in blood pressure; potassium (K^{+}) causes hyperkalemia, which leads to cardiac arrhythmias and nervous and digestive disorders; the long-term intake of calcium (Ca^{2+}) causes hypercalcemia, urinary tract stones, and calcification in the kidneys and artery walls [27,48]; and magnesium (Mg^{2+}) with sulfate ($SO_4{}^{2-}$) cause gastrointestinal disorders [27]. In addition, one of the most abundant anions in water that causes disease is sulfate ($SO_4{}^{2-}$), which can cause a laxative effect, causing diseases such as diarrhea [27,62].

On the other hand, aluminum, ammonium, chloride, copper, and iron, among others, can have adverse health effects depending on their levels and exposure. Although at lower concentrations these elements may go unnoticed, an increase in their levels can trigger several health problems, which is why it is important to control and maintain these elements within acceptable limits to guarantee the safety of drinking water supplies and prevent possible health risks [15,27]

According to the literature, most heavy metals are generally toxic to the body, and their health effects can vary depending on the time of exposure. Specifically, lead, arsenic, cadmium, and mercury are carcinogenic [48]; additionally, chromium (III) and (VI), cadmium, nickel, copper, zinc, arsenic, and lead are highly soluble in water and can be absorbed by aquatic organisms, thus accumulating in the human body not only through drinking water but also through the food chain [43]. In addition to carcinogenic effects, they can cause teratogenic effects, act as endocrine disruptors of heavy metals, and, crucially, lead to negative changes in the health and behavior of children [43].

In the dry season, the availability of surface water for consumption is reduced, so pollutants are concentrated in existing water sources, forcing the population to use groundwater resources even in areas where the underlying aquifers may have high levels of heavy metals such as arsenic or even radioactive chemicals [56].

Tables 7–9 provide the results of organic chemical parameters of water quality for human consumption related to different diseases.

Table 7. Organic chemical parameters related to cardiovascular and endocrine diseases.

Parameter/ Diseases	Cardiovascular			Endocrinology								
	Cardiovascular/ Circulatory System	Spleen Problems	Arteriosclerosis	Decrease in Blood Sugar	Thyroid Problems	Hair or Fingernail Loss	Reproductive Problems	Adrenal Gland Problems	Weight Loss	Thymus Gland Problems	Pancreatic Diseases	Diabetes
Alachlor		[14]										
Atrazine	[14]						[14]					
Benzo(a)pyrene (PAHs)							[14]					
Carbofuran							[14]					
2,4-D								[14]				
1,2-Dibromo-3-chloropropane (DBCP)							[14]					
o-Dichlorobenzene	[14]											
p-Dichlorobenzene		[14]										
Di(2-ethylhexyl)adipate							[14]		[14]			
Di(2-ethylhexyl)phthalate							[14]					

Table 7. *Cont.*

Parameter/ Diseases	Cardiovascular			Endocrinology								
	Cardiovascular/ Circulatory System	Spleen Problems	Arteriosclerosis	Decrease in Blood Sugar	Thyroid Problems	Hair or Fingernail Loss	Reproductive Problems	Adrenal Gland Problems	Weight Loss	Thymus Gland Problems	Pancreatic Diseases	Diabetes
Dinoseb							[14]					
Dioxin (2,3,7,8-TCDD)							[14]					
Ethylene dibromide							[14]					
Glyphosate							[14]					
Hexachlorobenzene							[14]					
Methoxychlor							[14]					
Polychlorinated biphenyls (PCBs)							[14]			[14]		
Styrene	[14]											
Toxaphene					[14]							
1,2,4-Trichlorobenzene								[14]				
1,1,1-Trichloroethane	[14]											
Organic compounds (pesticides)	[27]						[14,27]					
PFAS (per- and polyfluoroalkyl substances)					[16]							

Table 8. Organic chemical parameters related to neurological, renal, gastrointestinal, and hematological diseases.

Parameter/ Diseases	Neurological	Renal	Gastrointestinal			Hematology		
	Neurological Symptoms	Kidney Dysfunction Problems Urinary Tract Disease	Gastrointestinal Illness	Vomiting	Stomach Problems	Anemia	Blood Problems Changes in Blood	Infantile Methemoglobinemia
Haloacetic acids (HAAs)								
Total Trihalomethanes (TTHMs)	[14]	[14]						
Chloramines (as Cl_2)					[14]	[14]		
Acrylamide	[14]							[14]
Alachlor		[14]				[14]		
Benzene						[14]	[14]	
Carbofuran	[14]						[14]	
Chlordane	[14]							
Chlorobenzene		[14]						
2,4-D		[14]						

Table 8. *Cont.*

Parameter/ Diseases	Neurological	Renal	Gastrointestinal			Hematology		
	Neurological Symptoms	Kidney Dysfunction Problems Urinary Tract Disease	Gastrointestinal Illness	Vomiting	Stomach Problems	Anemia	Blood Problems Changes in Blood	Infantile Methemoglobinemia
Dalapon		[14]						
o-Dichlorobenzene		[14]						
p-Dichlorobenzene		[14]				[14]	[14]	
Endothall			[14]		[14]			
Epichlorohydrin					[14]			
Ethylbenzene		[14]						
Ethylene dibromide		[14]			[14]			
Glyphosate		[14]						
Hexachlorobenzene		[14]						
Hexachlorocyclopentadiene		[14]			[14]			
Lindane		[14]						
Oxamyl (Vydate)	[14]							
Polychlorinated biphenyls (PCBs)	[14]							
Pentachlorophenol		[14]						
Simazine							[14]	
Styrene		[14]						
Toluene	[14]	[14]						
Toxaphene		[14]						
1,1,1-Trichloroethane	[14]							
1,1,2-Trichloroethane		[14]						
Xylenes (total)	[14]							
Organic compounds (pesticides)	[27]	[14]		[27]				

Table 9. Organic chemical parameters related to hepatic, dermatological, rheumatic, immunological, pneumological, allergy-related, oncological, and ophthalmological diseases.

Parameter/ Diseases	Liver	Dermatology	Rheumatology	Immunology		Pneumology				Allergology	Oncology	Ophthalmology	
	Liver Diseases	Skin Diseases	Numbness in Fingers or Toes	Immune Deficiencies	Fever	Contamination by Nitrites	Legionnaires Disease	Lung Diseases	Nose Irritation	Allergic Dermatitis	Cancer Risk	Eye Problems	Cataracts
Haloacetic acids (HAAs)											[14,16,63,64]		
Total trihalomethanes (TTHMs)	[14]										[14,16,56,63–65]		
Chloramines (as Cl_2)									[14]			[14]	
Acrylamide											[14]		

Table 9. *Cont.*

Parameter/ Diseases	Liver	Dermatology	Rheumatology	Immunology		Pneumology				Allergology	Oncology	Ophthalmology	
	Liver Diseases	Skin Diseases	Numbness in Fingers or Toes	Immune Deficiencies	Fever	Contamination by Nitrites	Legionnaires Disease	Lung Diseases	Nose Irritation	Allergic Dermatitis	Cancer Risk	Eye Problems	Cataracts
Alachlor	[14]										[14]	[14]	
Atrazine													
Benzene											[14]		
Benzo(a)pyrene (PAHs)											[14]		
Carbon tetrachloride	[14]										[14]		
Chlordane	[14]										[14]		
Chlorobenzene	[14]												
2,4-D	[14]												
1,2-Dibromo-3-chloropropane (DBCP)											[14]		
o-Dichlorobenzene	[14]												
p-Dichlorobenzene	[14]												
1,2-Dichloroethane											[14]		
1,1-Dichloroethylene	[14]												
cis-1,2-Dichloroethylene	[14]												
trans-1,2-Dichloroethylene	[14]												
Dichloromethane	[14]										[14]		
1,2-Dichloropropane											[14]		
Di(2-ethylhexyl)adipate	[14]												
Di(2-ethylhexyl)phthalate	[14]										[14]		
Dioxin (2,3,7,8-TCDD)											[14]		
Diquat													[14]
Endrin	[14]												
Epichlorohydrin											[14]		
Ethylbenzene	[14]												
Ethylene dibromide	[14]										[14]		
Glyphosate													
Heptachlor	[14]										[14]		
Heptachlor epoxide	[14]										[14]		
Hexachlorobenzene	[14]										[14]		
Lindane	[14]												
Polychlorinated biphenyls (PCBs)		[14]		[14]							[14]		
Pentachlorophenol	[14]										[14]		
Picloram	[14]												
Styrene	[14]												
Tetrachloroethylene	[14]										[14]		
Toluene	[14]												
Toxaphene	[14]										[14]		

Table 9. *Cont.*

Parameter/ Diseases	Liver	Dermatology	Rheumatology	Immunology		Pneumology				Allergology	Oncology	Ophthalmology	
	Liver Diseases	Skin Diseases	Numbness in Fingers or Toes	Immune Deficiencies	Fever	Contamination by Nitrites	Legionnaires Disease	Lung Diseases	Nose Irritation	Allergic Dermatitis	Cancer Risk	Eye Problems	Cataracts
2,4,5-TP (Silvex)	[14]												
1,1,1-Trichloroethane	[14]												
1,1,2-Trichloroethane	[14]			[14]									
Trichloroethylene	[14]										[14]		
Vinyl chloride											[14]		
Organic compounds (pesticides)								[27]			[56]		
PFAS (per- and polyfluoroalkyl substances)											[16]		

Other organic chemical parameters like pesticides are related to health diseases. There is little information in the literature on the health effects of contaminated drinking water, only studies on organic compounds and their impact on health, especially carcinogenic diseases, as discovered through animal testing. However, it is known that after a pesticide is applied to soil, runoff and sediment may reach the nearest water bodies, contaminating water sources, and bioaccumulating in the food chain [27].

According to the U.S. Environmental Protection Agency, most of these organic compounds are carcinogenic [14]. In addition, some can cause developmental disorders in children, attention deficit disorders, and other symptoms of poisoning such as vomiting, nausea, blurred vision, and breathing difficulties [27].

In other research, it was found that tetrachloroethylene has possible effects on pregnant mothers, causing a risk of fetal death; this was tested through a model incorporating information from women exposed to this organic compound via drinking water for about three decades [66].

The most common disinfection byproducts come from chlorine disinfection and its reaction with organic matter present in drinking water. These are total trihalomethanes (chloroform, bromoform, dibromochloromethane, and bromodichloromethane) and haloacetic acids (monochloroacetic acid, dichloroacetic acid, monobromoacetic acid, dibromoacetic acid, and trichloroacetic acid). Long-term exposure to TTHMs and HAAs is associated with the risk of cancer, especially bladder cancer, while maternal exposure (stage of pregnancy), which resulted in risk to the fetus, yielded mixed outcomes [16,67,68].

The concentration of disinfection byproducts in drinking water is influenced by several factors, such as seasonal fluctuations, temperature, and pH. Disinfection by-products tend to show higher concentrations in the dry season than the rainy season; pH, whether high or low, influences the generation of trihalomethanes and haloacetic acids, respectively; and temperature, if high, accelerates the reaction of organic matter and chlorine increasing trihalomethanes formation [16,64].

It is important to mention that PFAS (per- and polyfluoroalkyl substances) are emerging pollutants of chemical origin, having been recently identified and lacking regulation. Exposure to drinking water is associated with thyroid disease, decreased weight in newborns, and testicular and kidney cancer [16].

Table 10 provides the results of radionuclide parameters of water quality for human consumption related to different diseases.

Table 10. Radionuclide parameters related to cardiovascular, endocrine, oncological, and renal diseases.

Parameter/ Diseases	Cardiovascular	Endocrinology	Oncology	Renal
			Cancer Risk	Kidney Dysfunction Problems
Alpha particles			[14]	
Beta particles and photon emitters			[14]	
Radium 226 and Radium 228 (combined)			[14]	
Uranium	[69]	[14,69]	[14,69]	[14,69]

Radionuclides in water used for human consumption, including alpha particles, beta particles, photon emitters, Radium 226, Radium 228, and uranium, are critically linked to various health issues, as noted in Table 10. These radioactive substances can pose significant risks when present in drinking water. Alpha particles, when ingested or inhaled, can lead to lung and bone cancers. Beta particles may cause skin burns and, upon ingestion, can damage internal organs and increase cancer risk. Photon emitters are associated with cancers and blood disorders due to their effect on bone marrow. Radium 226 and Radium 228, which accumulate in bones, are particularly dangerous as they can cause bone cancer and other radiation-induced diseases. Uranium exposure can result in kidney damage and heightened cancer risk due to uranium's chemical toxicity and radioactivity. Therefore, maintaining stringent standards for radionuclide levels in drinking water is essential to safeguard public health.

3.2. Case Study: Tonosí

In the district of Tonosí, the drinking water provided to the population comes from both surface and underground sources. For the most part, communities use the catchments of surface water as their supply. However, due to the scarcity of drinking water, especially in the dry season, another part of the population chooses to drill and install communal wells.

Water quality was measured based on the conventional parameters established in the DGNTI-COPANIT 21-2019 Technical Regulations, which include physicochemical, inorganic chemicals, and biological; in addition, unconventional parameters, including heavy metals and organic compounds are measured due to the agricultural activity in the area.

Table 11 provides the water quality parameters that were beyond the permissible limits according to the DGNTI-COPANIT 21-2019 Technical Regulations for drinking water in Tonosí, Panama, and their associated diseases according to the results in Tables 1–10. Table 12 provides the water quality parameters that exceed the health-based guideline value of the World Health Organization (WHO) and their associated diseases according to the results in Tables 1–10.

Data on water quality parameters measured during the rainy and dry seasons, including pH, conductivity, color, turbidity, residual chlorine, hardness, and fecal coliform levels, are presented. The results indicate that some of these parameters exceed the permissible limits. Both Tables 11 and 12 show the symbol (+) for values that are above the allowed value and (−) for values that are below the minimum required, according to the values established by the DGNTI-COPANIT 21-2019 Technical Regulations for drinking water and by the World Health Organization, respectively.

Table 11. Drinking water quality according to DGNTI-COPANIT 21-2019 Technical Regulations for drinking water and associated diseases.

Water Quality Parameter Evaluated	**Tour 1 (Rainy Season)**	**Tour 2 (Dry Season)**	**Tour 3 (Dry Season)**	**Tour 4 (Rainy Season)**	**Permissible limits DGNTI-COPANIT 21-2019**	**Associated Diseases**
Water temperature						
pH	–	–		–	6.5–8.5	Affects the reabsorption of calcium and magnesium in the renal tubule of the kidney, and cancer.
Conductivity	+	+	+	+	850 µS/cm	Cancer, cardiovascular diseases, diseases of the nervous system, kidney diseases, diseases of the reproductive system, problems of the digestive system, and weakness in bones and teeth.
Dissolved oxygen						
Total dissolved solids						
Color	+	+	+	+	15 Pt/Co	Gastrointestinal diseases.
Turbidity	+	+	+	+	1 NTU	Gastrointestinal diseases.
Free residual chlorine	–	–	–	–	0.3–0.8 mg/L	Gastrointestinal diseases.
Phosphate						
Nitrate						
Nitrite						
Ammonium						
Sulfate						
Suspended solids						
Chloride						
Alkalinity						
Hardness	+	+	+	+	200 mg/L	Cancer, cardiovascular diseases, diseases of the nervous system, kidney diseases, diseases of the reproductive system, problems of the digestive system, and weakness in bones and teeth.
Acidity						
VOCs and pesticides						
Fecal coliform	+	+	+	+	<1 CFU/100 ml	Vomiting, diarrhea, abdominal cramps, and fever. Gastrointestinal diseases.
Elements and heavy metals	+	+	+	+	0.05 mg/L Cr 0.07 mg/L Ni 0.07 mg/L Ba 1 mg/L Cu 0.1mg/L Mn 0.02 mg/L Sb	Cancer, cardiovascular diseases, diseases of the nervous system, kidney diseases, diseases of the reproductive system, problems of the digestive system, weakness in bones, and gastrointestinal diseases.

Table 12. Drinking water quality, according to the WHO, and associated diseases.

Water Quality Parameter Evaluated	Tour 1 (Rainy Season)	Tour 2 (Dry Season)	Tour 3 (Dry Season)	Tour 4 (Rainy Season)	Permissible Limits Guidelines for Drinking-Water Quality (WHO)	Associated Diseases
Water temperature						
pH						
Conductivity						
Dissolved oxygen						
Total dissolved solids						
Color						
Turbidity						
Free residual chlorine	–	–	–	–	0.2–0.5 mg/L	Gastrointestinal diseases.
Phosphate						
Nitrate						
Nitrite						
Ammonium						
Sulfate						
Suspended solids						
Chloride						
Alkalinity						
Hardness						
Acidity						
VOCs and pesticides						
Fecal coliform	+	+	+	+	0 CFU/100 mL	Vomiting, diarrhea, abdominal cramps, and fever. Gastrointestinal diseases.
Elements and heavy metals	+	+	+	+	0.05 mg/L Cr 0.07 g/L Ni 1.3 mg/L Ba 1 mg/L Cu 0.08 mg/L Mn 0.02 mg/L Sb	Cancer, cardiovascular diseases, diseases of the nervous system, kidney diseases, diseases of the reproductive system, problems of the digestive system, weakness in bones, and gastrointestinal diseases.

Both Tables 11 and 12 show similar values in the maximum permissible limits for fecal coliforms and heavy elements and metals. According to the WHO, no health-based guideline value is proposed for pH, color, and hardness because those parameters do not have a direct impact on the health of the consumer [15]. However, the guidelines for drinking water quality mention that the optimal pH required will vary in different supplies according to the composition of the water and nature, but it is usually in the range of 6.5 to 8.5. It also mentions that color levels below 15 Pt/Co are often acceptable to consumers and that, in some cases, consumers tolerate water hardness above 500 mg/L [15], showing similar values to Panamanian regulations.

However, the parameters measured are indicators of the presence of disease-causing agents (acute or chronic), depending on their length of exposure time.

pH does not have a direct impact on health. However, the acidity of the water affects the reabsorption of calcium and magnesium in the renal tubule of the kidney [43], and the low pH in the water could be related to the geology of the area, climatic variations, abundance of rainfall in the rainy season or mining activity, in which the presence of heavy metals can cause various health problems, such as cancer [48].

The minerals and heavy metals found in water sources were chromium, copper, nickel, iron, manganese, aluminum, and antimony. Exposure through drinking water affects human health differently, causing short-term to long-term diseases [27,44,48]. The chromium found does not reveal whether it is chromium (VI), toxic to human health, which should prioritize the continuity of analysis of this parameter by the speciation method, which can be completed by the inductively coupled plasma mass spectrometry (ICP-MASS) technique or spectrophotometry.

Hardness and conductivity do not have any direct impact on health. However, they are indicators of the concentration of ions in water. Hardness is caused by calcium and magnesium ions [43], and their high levels can lead to heart disease [47]. In addition, increased water hardness is the cause of cancer, cardiovascular diseases, diseases in the different systems of the human body, and weakness in bones and teeth [43,70].

The results of the sampling tours show that color and turbidity, despite yielding values above the allowed threshold in both climatic seasons, show higher values during the rainy season. Color, turbidity, and fecal coliform are indicators of water quality and are related to the presence of microorganisms that cause gastrointestinal diseases, and color and turbidity are also related to the presence of iron and other metals that cause vomiting and nausea [15].

The parameters of color, turbidity, and fecal coliform indicate the presence of microbials in the drinking water of the population. The free residual chlorine parameter, an indicator of the presence of chlorine in the water, does not reach the range of the limit established in the DGNTI-COPANIT 21-2019 Technical Regulations, which confirms that the water of the studied communities lacks a basic method of disinfection. Chlorine is a relatively inexpensive and accessible chemical, destroying most disease-causing organisms without endangering people. However, this chemical is consumed, which requires adding enough chlorine, leaving some in the water after all the organisms are eliminated. For this reason, if the water is tested and free residual chlorine is found, it is verified that most of the dangerous organisms have already been eliminated from the water and, therefore, it is safe to consume [71].

According to the Social Security Fund (C.S.S) and the Ministry of Health (MINSA), one of the most relevant epidemiological aspects in the province of Los Santos is water pollution [72]. Additionally, a document on the analysis of the health situation in the region revealed that one of the main causes of morbidity in the population, generally, is diarrhea and gastrointestinal diseases in children under 1 year of age [73]. This observation may reveal a relationship between the evaluated water quality and the associated disease because contaminated water is one of the main sources of disease transmission [26].

Other parameters that were found at the trace level included some volatile organic compounds such as xylene, toluene, and benzene, indicators of fuel residues, in a groundwater sample near the airport in the area. Traces of chloroform and chloropicrin were also found, these compounds are active substances of phytosanitary products, such as fungicides and insecticides around Tonosí cabecera. Although these values for these parameters fall below the maximum permissible levels, it is nevertheless important to communicate their presence and continue to monitor the water quality of these sources.

4. Discussion

The Republic of Panama does not have updated and detailed information on water quality conditions in many areas at the national level, nor does it have the location of many of the wells that are currently used for the supply of water for human consumption, nor exhaustive hydrological studies on the recharge zones and the dynamics or interaction between groundwater and surface water in the area. Therefore, water quality data in the district of Tonosí are scarce and scatter.

Currently, there is only information on the supply of drinking water and sanitation by districts, prepared by the National Institution of Statistics and Census for 2023, which reflects results of the conditions of basic services in the district of Tonosí, showing that 74% of the population uses public aqueducts managed by the community, that in many cases their management is deficient, 15% of the population uses aqueducts supplied by the Institute of National Aqueducts and Sewers (IDAAN) and 11% obtains water in an artisanal way (rivers, streams and mouth wells) [74]. In addition, it is known that the sanitary service system is deficient, where 81% of the population is connected to a septic tank, 17% uses latrines, 2% do not have a sanitary service, and only 0.5% is connected to sewerage.

On the other hand, a study of the western region of Panama reveals that in areas where water pressure is inconsistent, water quality for irrigation is affected when pressure levels are lower, as it allows water from the environment to enter the pipes, raising the levels of total coliform and *E. coli* bacteria and decreasing residual levels of free chlorine, and also allows the intrusion of contaminated groundwater through leaks in the pipes [75].

The results obtained for the biological parameters and physicochemical parameters show that there is a relationship between water quality and gastrointestinal diseases in the study area due to water supply conditions and climatic events.

According to the World Health Organization, pathogens (viruses, bacteria, and parasites) mainly cause gastroenteritis, and these cases are due to the consumption of water contaminated by feces (human and animal) and are attributed to the specific microorganisms or toxins they generate [15,76].

Additionally, hardness is another parameter that was evaluated and found to fall outside the permissible range specified in the Technical Regulations. It is known that in the provinces of Coclé and Darién and in the Azuero Peninsula, the area where the district of Tonosí is located, groundwater is scarce and has high levels of salinity and hardness [77].

As mentioned above, hardness in drinking water is a result of the amount of dissolved calcium and magnesium. According to some authors, calcium is associated with cardiovascular and kidney diseases, and magnesium with gastrointestinal diseases, and high levels of hardness in water produce cancer and various diseases in the systems of the human body [27,43,47].

According to the report of the Social Security Fund (C.S.S), one of the main chronic noncommunicable diseases in Los Santos is related to the cardiovascular system [73]. In this case, it is not possible to establish a direct relationship between this disease and the quality of the water; however, the consumption of water with high levels of hardness contributes to diseases related to the cardiovascular system.

Evans [56] explains that compliance with drinking water standards does not mean that the levels of contaminants in the water are reduced to concentrations that pose no health risks; indeed, the most cancer risk and estimated lifetime cancer cases are from community water systems that fully meet drinking water standards.

In addition, there is a cumulative risk of cancer from groundwater consumption due to the concentration of heavy metal contaminants such as arsenic, disinfection byproducts, and radioactive contaminants [56].

Other authors, such as Ward and Schullehner, demonstrate that there is an increased risk of colorectal cancer at nitrate concentrations in drinking water below the current drinking water standard [46,55]. Schaider et al. also explain that nitrate is commonly found in drinking water, especially in agricultural regions, and epidemiological evidence suggests an elevated risk of cancer, even at levels below the standard for drinking water [78]. The risks related to nitrate are more prevalent in Europe, where the maximum permissible value is 50 mg/L. Denmark is one of the countries with the most studies relating to nitrate due to its dedication to agricultural activity [79,80]. Therefore, populations that use groundwater sources are prone to unknowingly developing diseases due to contamination by inorganic chemicals.

Knowing this, given that high levels of organic compounds were not found in Tonosí, further water quality monitoring and studies are needed to determine if organic compounds occur in water sources and if the morbidity of the population is related to the consumption of contaminated drinking water due to agricultural activity in the area.

Water resources, especially groundwater resources in Panama, are not well studied, and their recharge zones and characteristics, such as transmissivity, hydraulic conductivity, recharge rates, pollution sources, saline intrusion (for coastal aquifers), and hydrogeochemistry are poorly understood [20,77].

There are few studies on surface and groundwater sources in Panama, together with a scarcity of information on morbidity in the country; however, the results obtained in the research on the quality of drinking water in Tonosí demonstrate the presence of contaminants in water sources and the comparison with studies carried out by authors who present similar cases on diseases caused by biological, organic and inorganic chemical parameters and physicochemical parameters present in drinking water, shows that there is a contribution of drinking water to the development of diseases, due to immediate and prolonged exposure to water in the study area.

5. Conclusions

Worldwide, the contamination of water resources is evident, and adequate water treatment is necessary before public consumption. In this study, several diseases that are correlated with the quality of drinking water, according to the literature, were identified.

The main threats of contamination are from bacteria, viruses, and parasites that can survive in poor environmental conditions, such as in degraded sediments and soil, which are often resistant to chlorine disinfection. Other contaminants include heavy metals found naturally in soil, but high concentrations and prolonged consumption of drinking water can lead to chronic diseases, such as cancer. During the research, organic and inorganic chemical and biological parameters were found whose levels or presence could be associated with the pathologies described in the aforementioned references.

In addition, in areas such as Tonosí, where the main economic activity is agriculture, traces of organic compounds in the soil and in the water are possible due to runoff, which causes serious diseases related to water consumption. Drinking water with traces of organic chemicals is known to be toxic and can cause cancer. However, there are few studies on organic chemicals and their relationship to human health. In contrast, it was found that water resources have minerals that are important for human health, but their excessive consumption can lead to diseases. In addition, there are other contaminants in drinking water that can influence the morbidity of the population, such as radionuclides and disinfection derivatives, but these need to be studied further.

In Panama, the lack of studies, monitoring, supervision, and compliance with laws are the main factors leading to water pollution. Furthermore, the little information available and the scarcity of statistics on diseases in the country are factors that put the population at risk due to misinformation on health issues, and both prevent a more detailed study of the current situation in terms of water quality and associated morbidity.

Performing more studies on pollutants in water sources is recommended because water is the main foundation for human health, and it is proposed that Panama's government carry out activities that promote scientific research and the remediation of the country's water resources.

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