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Mortality and Years of Life Lost from Waterborne and Water-Related Infectious Diseases in Costa Rica, 2000–2023: A Nationwide Ecological Study

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Abstract

Waterborne, water-related, and foodborne infectious diseases remain preventable causes of mortality, but long-term evidence on their demographic, spatial, and premature mortality burden is limited in Costa Rica. This ecological population-based study described deaths classified under selected ICD-10 codes during 2000–2023 using official mortality and population data. Crude and age-standardized mortality rates, years of life lost (YLL), and YLL rates were estimated by time, sex, age group, and geographic area. A total of 2450 deaths were identified. Diarrhea and gastroenteritis of presumed infectious origin accounted for 1537 deaths (62.7%), followed by other bacterial intestinal infections (23.8%) and leptospirosis (7.0%). Annual crude mortality rates ranged from 1.28 per 100,000 population in 2021 to 3.03 in 2017. Mortality showed a bimodal age pattern, with the highest rate among persons aged 75 years or older and a relevant early-childhood component. A total of 57,625.5 YLL were estimated, with the largest burden among children aged 0–4 years and the highest provincial YLL rates in Limón, Puntarenas, and Guanacaste. These findings support incorporating premature mortality metrics into environmental health surveillance, although the ecological design does not identify exposure sources or causal determinants.

Keywords: waterborne diseases; diarrheal diseases; mortality; years of life lost; age-standardized mortality rate; Costa Rica; environmental health surveillance; sanitation



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1. Introduction

Despite substantial progress in reducing mortality associated with diarrheal diseases and inadequate water, sanitation, and hygiene (WASH), waterborne and sanitation-related infections remain a major global public health problem. The Global Burden of Disease 2021 Study estimated that diarrhoeal diseases caused 1.17 million deaths and 59 million disability-adjusted life years globally in 2021, despite marked reductions in mortality since 1990 [1]. However, the decline in incidence and prevalence has been less pronounced, indicating that transmission and morbidity remain persistent worldwide. Children and older adults continue to be among the most vulnerable groups: diarrheal diseases remain an important cause of death among children under five years of age in low- and middle-income countries, while older adults also experience substantial morbidity and mortality due to gastrointestinal infections and related complications [2,3].

Waterborne infectious diseases are caused by a heterogeneous group of bacterial, viral, and parasitic pathogens. Bacterial agents such as *Shigella* spp., *Vibrio cholerae*, *Salmonella* spp., *Campylobacter jejuni*, and diarrhoeagenic *Escherichia coli* are major contributors to diarrheal morbidity and mortality, particularly in settings with unsafe water or inadequate sanitation. Viral pathogens, including rotavirus, norovirus, and hepatitis A virus, also contribute substantially to the global burden of diarrheal disease. Norovirus alone is estimated to cause more than 120,000 deaths annually, with the most severe outcomes occurring in low-resource settings. Protozoan parasites such as *Giardia intestinalis*, *Cryptosporidium* spp., and *Entamoeba histolytica* are also frequently associated with waterborne infections, especially where fecal contamination of water sources persists [1,4,5]. Therefore, mortality categories such as infectious gastroenteritis and diarrhea may represent a syndromic burden involving multiple etiological agents rather than a single pathogen-specific outcome [6,7].

Tropical countries face additional challenges in the prevention of waterborne infections. Heavy rainfall, flooding, temperature variability, and extreme hydrometeorological events can affect water quality, sanitation infrastructure, pathogen survival, and human exposure. Previous studies have reported associations between rainfall, flooding, ENSO-related variability, tropical cyclones, temperature, and infectious disease transmission, although these relationships are often context-dependent and mediated by local infrastructure, land use, and sanitation conditions [8–13]. These factors are relevant for Central American countries, where tropical climate, rapid urbanization, land-use change, and heterogeneous sanitation infrastructure may create localized vulnerability despite favorable national indicators [12,14–16].

Costa Rica has achieved high drinking-water coverage compared with other countries in the region, with access to safe drinking water exceeding 90% in recent years [16]. Nevertheless, sanitation remains a structural challenge. A large proportion of excreta disposal is managed through septic tank systems, while centralized sewerage and secondary wastewater treatment remain limited [16,17]. In addition, population growth, urbanization, land-use change, and wastewater discharges may increase the vulnerability of surface waters and drinking-water sources to fecal contamination and microbial deterioration [14,15,18,19]. Thus, Costa Rica represents a relevant setting to study the residual mortality burden of waterborne infectious diseases in a middle-income country with high water coverage but persistent environmental and sanitation challenges [20,21].

Long-term national analyses of waterborne infectious disease mortality in Costa Rica remain limited, particularly those integrating temporal, demographic, spatial, and premature mortality dimensions. Mortality counts and crude rates are useful for describing the frequency of deaths, but they may obscure differences in age structure and the burden generated by deaths occurring early in life. Age-standardized mortality rates allow comparisons across populations with different age distributions, while years of life lost provide an estimate of premature mortality burden by weighting deaths according to remaining life expectancy [22,23]. These indicators can reveal patterns that are not evident from death counts alone.

In this study, mortality attributable to selected waterborne infectious diseases in Costa Rica was analyzed from 2000 to 2023 using official mortality and population data from the National Institute of Statistics and Censuses. The objective was to describe the temporal, demographic, and spatial distribution of waterborne infectious disease mortality and to estimate crude mortality rates, age-standardized mortality rates, and years of life lost by age, sex, and geographic area. This approach was used to identify vulnerable populations, characterize territorial differences, and provide evidence for strengthening environmental health surveillance, water safety, sanitation, and disease prevention strategies.

2. Materials and Methods

2.1. Study Design and Setting

An ecological, population-based mortality study was conducted to describe the burden of waterborne infectious disease mortality in Costa Rica from 2000 to 2023. The unit of analysis was defined at aggregated population levels according to calendar year, sex, age group, cause of death, and place of residence. This design was selected because the objective was to compare mortality frequencies, rates, and premature mortality burden across population groups defined by time and geographic location, rather than to estimate individual-level causal effects [24]. Ecological studies are appropriate for group-level inference and hypothesis generation, but they do not allow direct linkage between exposure and outcome at the individual level; therefore, results were interpreted at the population level to avoid ecological fallacy [24,25].

The methods and reporting structure were organized according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations, including explicit description of study design, setting, data sources, variables, bias, study size, quantitative variable handling, and statistical methods. Although STROBE was originally developed for cohort, case-control, and cross-sectional studies, its reporting principles are applicable for improving transparency in observational epidemiological studies [26].

2.2. Data Sources

Mortality data were obtained upon request from the national death registry of the Instituto Nacional de Estadística y Censos of Costa Rica (INEC). Death records were based on official death certificates and included sociodemographic, geographic, and cause-of-death information. INEC mortality statistics are produced continuously to describe the volume, trends, and characteristics of mortality in Costa Rica, including geographic, sociodemographic, and cause-specific variables [27]. Population denominators were obtained from INEC demographic population estimates and projections. Population data were used to calculate crude mortality rates, age-specific rates, age-standardized mortality rates, and Years of life lost (YLL) rates. The study population comprised the entire available Costa Rican population during the period 2000–2023; therefore, no sample-size calculation was performed.

2.3. Case Definition

Cases were defined as deaths registered between 2000 and 2023 in which the underlying cause of death corresponded to selected waterborne or water-related infectious diseases according to ICD-10 codes. The expanded case definition included deaths classified as cholera (A00), typhoid and paratyphoid fevers (A01), other *Salmonella* infections (A02), shigellosis (A03), other bacterial intestinal infections (A04), other bacterial foodborne intoxications (A05), amoebiasis (A06), other protozoal intestinal diseases (A07), viral and other specified intestinal infections (A08), diarrhea and gastroenteritis of presumed infectious origin (A09), leptospirosis (A27), or acute hepatitis A (B15). These codes were grouped into broader analytical categories to summarize the burden by disease group while preserving ICD-10 cause-specific information for descriptive analyses.

2.4. Variables

The main outcome was death due to a selected waterborne infectious disease. The primary descriptive variables were year of death, date of death, ICD-10 cause of death, disease group, sex, age, age group, county of residence, province, Greater Metropolitan Area status, and territorial slope classification. Age was grouped into 16 categories: 0–4, 5–9,

10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, and 75 years or older. Geographic variables were harmonized using standardized county names before joining mortality, population, and spatial data. County-level spatial analyses were based on the official county geometry file. Mortality and population data were joined to the spatial layer using standardized county names. County names were cleaned and harmonized to resolve spelling, accent, and administrative-name inconsistencies before calculating spatial rates.

2.5. Data Management

Mortality records were filtered by year and ICD-10 code. Cause-of-death groups were created from ICD-10 codes. Age groups were derived from age at death. Mortality data were aggregated by year, county, sex, age group, and cause, depending on the analysis. Population data were reshaped and joined to the mortality dataset using year, county, sex, and age group. Spatial joins were performed after county-name standardization. No imputation was applied. Completeness of key analytical variables was checked before aggregation.

2.6. Statistical Analysis

Descriptive analyses were performed using death counts, proportions, crude mortality rates, age-specific mortality rates, age-standardized mortality rates, years of life lost, YLL rates, and mean YLL per death. Results were summarized by year, sex, age group, cause of death, province, county, Greater Metropolitan Area status, and territorial slope [25,28]. The crude mortality rate was calculated as:

$$\text{Crude mortality rate}_{t,g} = \frac{D_{t,g}}{P_{t,g}} \times 100,000$$

where ($D_{t,g}$) is the number of deaths in year (t) and population group (g), and ($P_{t,g}$) is the corresponding population denominator [25,28].

Age-specific mortality rates were calculated as:

$$r_{a,t,g} = \frac{D_{a,t,g}}{P_{a,t,g}} \times 100,000$$

where ($D_{a,t,g}$) is the number of deaths in age group (a), year (t), and population group (g), and ($P_{a,t,g}$) is the corresponding age-specific population. Age-standardized mortality rates were estimated using direct standardization. The standard population was defined as the aggregated national population of Costa Rica during 2000–2023 across the same age groups used in the analysis. Direct standardization was used to reduce the influence of differences in age composition when comparing mortality rates across groups or over time. The method corresponds to a weighted average of age-specific rates, where weights are obtained from the age distribution of a standard population [29].

County-level spatial variation was assessed using indirect standardization and global empirical Bayes smoothing. Expected deaths were calculated for each county by applying national mortality rates specific to calendar year, sex, and age group to the corresponding county population in each stratum. Expected values were then summed across strata and years for the 2000–2023 period. The crude standardized mortality ratio (SMR) was calculated as the ratio of observed to expected deaths [30,31].

To reduce instability caused by sparse counts in small counties, a global empirical Bayes Poisson–Gamma model was fitted. Observed deaths in each county were assumed to follow a Poisson distribution conditional on the expected number of deaths and an underlying county-specific relative mortality parameter. The prior distribution of this parameter was specified as Gamma(α , α), with an expected value of 1, representing the

national mortality pattern after indirect standardization. The empirical Bayes parameter α was estimated by maximum marginal likelihood. Smoothed SMRs were calculated as posterior means, and 95% posterior credible intervals were obtained from the corresponding Gamma posterior distribution. Values above 1 indicated mortality above the national expected level after standardization by calendar year, sex, and age group, whereas values below 1 indicated mortality below the expected level. This global smoothing approach reduced small-area random variation but did not impose spatial dependence between neighboring counties [30,31].

Years of life lost (YLL) were estimated to quantify premature mortality. For each eligible death, YLL corresponded to the remaining life expectancy at the completed age of death, obtained from sex-specific provincial life tables published by the National Institute of Statistics and Censuses of Costa Rica (INEC) for the corresponding calendar year. Thus, YLL for an individual death was calculated as:

$$YLL_i = e_{p_i, t_i, s_i, a_i}$$

where (e_{p_i, t_i, s_i, a_i}) is the remaining life expectancy based on the province of residence (p_i), year of death (t_i), sex (s_i), and completed age (a_i). Deaths occurring at ages 100 years or older were assigned the remaining life expectancy of the open age group of 100 years or older. Deaths with missing or invalid age, sex, province, or year information were excluded from YLL estimation [32].

Total YLL for each analytical group was calculated as:

$$YLL_g = \sum_{i=1}^{n_g} YLL_i$$

Age groups were used only to aggregate and present results and were not used to assign individual YLL values. YLL rates were calculated using the sum of annual population estimates during 2000–2023 and are expressed per 100,000 person-years [22,33,34]:

$$YLL\ rate_g = \frac{YLL_g}{\sum_{t=2000}^{2023} P_{t,g}} \times 100,000$$

Mean YLL per death was calculated as:

$$Mean\ YLL\ per\ death_g = \frac{YLL_g}{D_g}$$

where (D_g) is the number of deaths in group (g).

2.7. Bias and Limitations

The main source of bias was the ecological nature of the study [24]. Because mortality and population data were analyzed at aggregated levels, individual-level associations could not be inferred. The study therefore supports population-level comparisons of mortality burden, rate differences, and premature mortality patterns, but it does not establish individual-level causality or individual risk [24,29]. Potential misclassification of the cause of death was also possible because analyses depended on the accuracy of death certification and ICD-10 coding. Although date of death was available at daily resolution, the study did not evaluate short-term temporal associations with environmental exposures. Consequently, temporal and geographic patterns should not be interpreted as evidence of specific climatic or environmental determinants. County-level empirical Bayes

estimates were interpreted as relative mortality patterns rather than evidence of specific environmental, sanitation, or socioeconomic exposures.

2.8. Software

All data management, statistical analyses, and visualizations were conducted in R. Spatial processing was performed using county-level geographic data, and all rates were calculated after joining mortality counts with the corresponding population denominators.

3. Results

3.1. Overall Mortality Burden and Cause Distribution

A total of 2450 deaths attributable to waterborne infectious diseases were identified in Costa Rica during 2000–2023, corresponding to a mean of 102.1 deaths per year. Most deaths were concentrated in a small number of causes. Infectious gastroenteritis and diarrhea were the leading categories, with 1537 deaths (62.7%), followed by other bacterial intestinal infections with 582 deaths (23.8%) and leptospirosis with 172 deaths (7.0%). Other causes individually contributed less than 3% of deaths, including viral and other specified intestinal infections (2.5%), shigellosis (1.6%), other *Salmonella* sp. infections (0.9%), hepatitis A (0.7%), amoebiasis (0.3%), bacterial foodborne intoxications (0.2%), protozoal intestinal diseases (0.1%), cholera (0.1%), and typhoid/paratyphoid fevers (0.1%) (Table 1). At the broader group level, core waterborne infectious diseases accounted for 2234 deaths (91.2%).

Table 1. Deaths classified under selected ICD-10 codes for waterborne, water-related, and foodborne infectious diseases, Costa Rica, 2000–2023.

ICD-10 Code and Condition	Analytical Classification and Epidemiological Scope	Deaths, <i>n</i> (%)
A00—Cholera	Enteric/diarrheal infection; typically food- or water-related	2 (0.1)
A01—Typhoid and paratyphoid fevers	Enteric/diarrheal infection; fecal–oral, food- or water-related transmission	2 (0.1)
A02—Other <i>Salmonella</i> infections (non-typhoidal salmonellosis)	Food/water-related bacterial infection; commonly foodborne	21 (0.9)
A03—Shigellosis	Enteric/diarrheal infection; fecal–oral, food- or water-related transmission	39 (1.6)
A04—Other bacterial intestinal infections	Broad enteric category; pathogen not identified in mortality coding	582 (23.8)
A05—Other bacterial foodborne intoxications	Foodborne infection; not necessarily waterborne	6 (0.2)
A06—Amoebiasis	Enteric/protozoal infection; potentially food- or water-related	7 (0.3)
A07—Other protozoal intestinal diseases	Broad enteric/protozoal category; potentially food- or water-related	3 (0.1)
A08—Viral and other specified intestinal infections	Broad enteric category; transmission route not identifiable from mortality coding	62 (2.5)
A09—Diarrhea and gastroenteritis of presumed infectious origin	Syndromic enteric/diarrheal category; etiologically nonspecific	1537 (62.7)
A27—Leptospirosis	Water-related zoonotic infection; exposure to contaminated water or soil	172 (7.0)
B15—Acute hepatitis A	Food/water-related viral infection; fecal–oral transmission	17 (0.7)
	All selected ICD-10 codes	2450 (100.0)

3.2. Temporal Patterns

Annual mortality varied across the study period. Death counts ranged from 60 in 2008 to 150 in 2017, while annual crude mortality rates ranged from 1.28 deaths per

100,000 population in 2021 to 3.03 per 100,000 population in 2017 (Figure 1). Relatively lower annual counts and rates were observed between 2006 and 2012, with the minimum occurring in 2008, whereas higher values were recorded from 2013 to 2018 and peaked in 2017. Mortality subsequently declined to 78 deaths in 2020 and 66 deaths in 2021, followed by a modest increase to 81 deaths in 2022 and 89 deaths in 2023. These temporal patterns were descriptive and were not interpreted as statistically tested long-term trends.

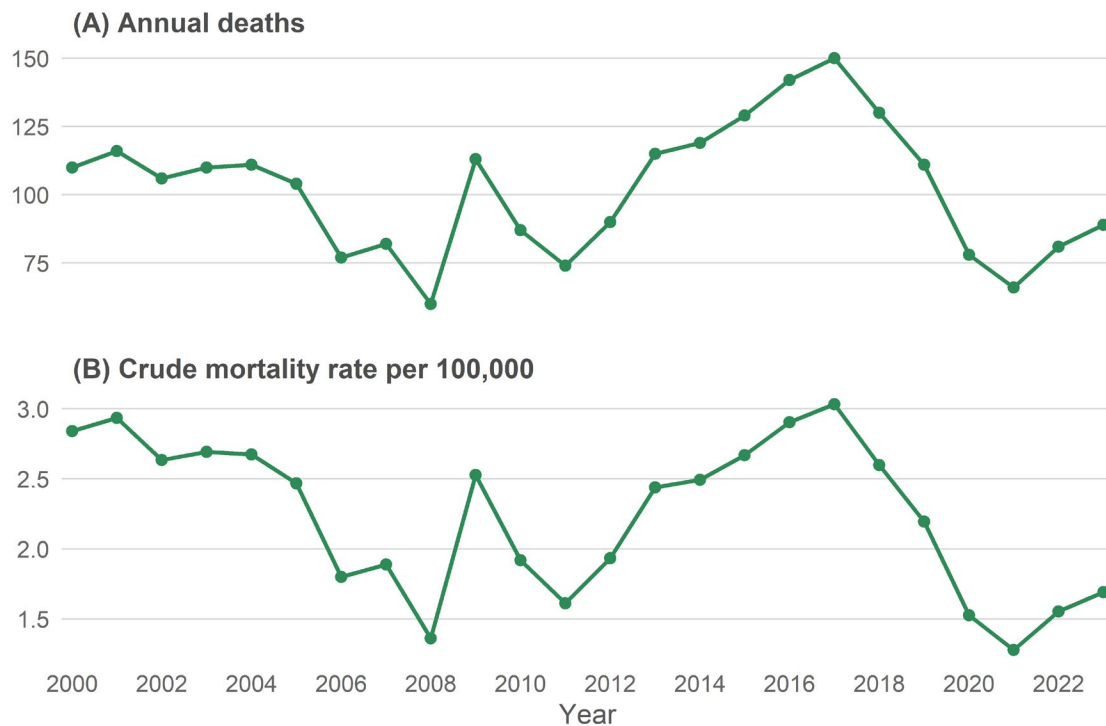


Figure 1. Annual mortality burden attributable to waterborne infectious diseases in Costa Rica, 2000–2023. (A) Annual deaths; (B) crude mortality rate per 100,000 population.

When grouped into three calendar periods, the highest cumulative crude mortality rate was observed during 2000–2007, with 816 deaths and a rate of 2.48 per 100,000 person-years. During 2008–2015, 787 deaths were recorded, corresponding to a cumulative crude mortality rate of 2.13 per 100,000 person-years. The period 2016–2023 accounted for the highest number of deaths ($n = 847$) but had the lowest cumulative crude mortality rate (2.08 per 100,000 person-years).

3.3. Demographic Distribution and Standardized Mortality

Females accounted for 1257 deaths (51.3%) and males for 1193 deaths (48.7%). Among deaths with non-missing age information, the median age at death was 74 years (IQR: 52–85) (Table 2). Females had a higher median age at death than males, 77 years (IQR: 60–86), in contrast with 70 years (IQR: 44–84). Age-specific mortality followed a J-shaped pattern. The 75+ age group accounted for the largest number of deaths, with 1201 deaths and the highest mortality rate, 38.65 per 100,000. The 0–4 age group accounted for 265 deaths and had a mortality rate of 2.99 per 100,000, higher than most age groups below 60 years. Mortality rates increased progressively after midlife, from 1.32 per 100,000 at ages 50–54 to 9.63 per 100,000 at ages 70–74, before reaching the maximum in the 75+ group.

Age-standardized mortality rates were estimated using 2412 deaths with non-missing age information. The national annual age-standardized mortality rate ranged from 1.09 per 100,000 in 2021 to 3.42 per 100,000 in 2001. Standardized rates were higher during the early years of the study period and remained comparatively lower after 2018. Pooled

age-standardized mortality was slightly higher among males (2.23 per 100,000) than among females (2.13 per 100,000), despite females having a higher crude mortality rate (Table 2).

Table 2. Summary of demographic and age-standardized mortality indicators, Costa Rica, 2000–2023.

Indicator	Estimate
Total deaths	2450
Female deaths	1257 (51.3%)
Male deaths	1193 (48.7%)
Deaths with non-missing age information	2412
Median age at death	74 years (IQR: 52–85)
Median age at death, female	77 years (IQR: 60–86)
Median age at death, male	70 years (IQR: 44–84)
Age group with highest number of deaths	75+ years
Deaths in 75+ age group	1201
Mortality rate in 75+ age group	38.65 per 100,000
Deaths in 0–4 age group	265
Mortality rate in 0–4 age group	2.99 per 100,000
Mortality rate in 50–54 age group	1.32 per 100,000
Mortality rate in 70–74 age group	9.63 per 100,000
Lowest annual ASMR	1.09 per 100,000, 2021
Highest annual ASMR	3.42 per 100,000, 2001
Pooled ASMR, female	2.13 per 100,000
Pooled ASMR, male	2.23 per 100,000

ASMR: age-standardized mortality rate; IQR: interquartile range.

The annual age-specific crude mortality heatmap confirmed the persistence of high mortality rates among older adults throughout the study period, particularly in the 75+, 70–74, and 65–69 groups (Figure 2). The 0–4 age group also showed consistently elevated crude mortality relative to most childhood, adolescent, and young adult groups, supporting the presence of a bimodal demographic burden: high mortality among older adults and a relevant early-childhood component.

3.4. Spatial Distribution

Cumulative crude mortality rates were highest in Puntarenas (2.65 per 100,000 person-years), San José (2.52 per 100,000 person-years), and Limón (2.37 per 100,000 person-years). The lowest crude rates were observed in Heredia (1.73 per 100,000 person-years) and Alajuela (1.66 per 100,000 person-years). After direct age standardization, the highest mortality rates were observed in Puntarenas (2.71 per 100,000 person-years) and Limón (2.61 per 100,000 person-years). A total of 1327 deaths occurred inside the Greater Metropolitan Area, corresponding to a cumulative crude mortality rate of 2.26 per 100,000 person-years, whereas 1123 deaths occurred outside the Greater Metropolitan Area, with a crude rate of 2.16 per 100,000 person-years. However, the age-standardized pattern was reversed: areas outside the Greater Metropolitan Area showed a higher age-standardized mortality rate than areas inside it (2.21 versus 2.12 per 100,000 person-years).

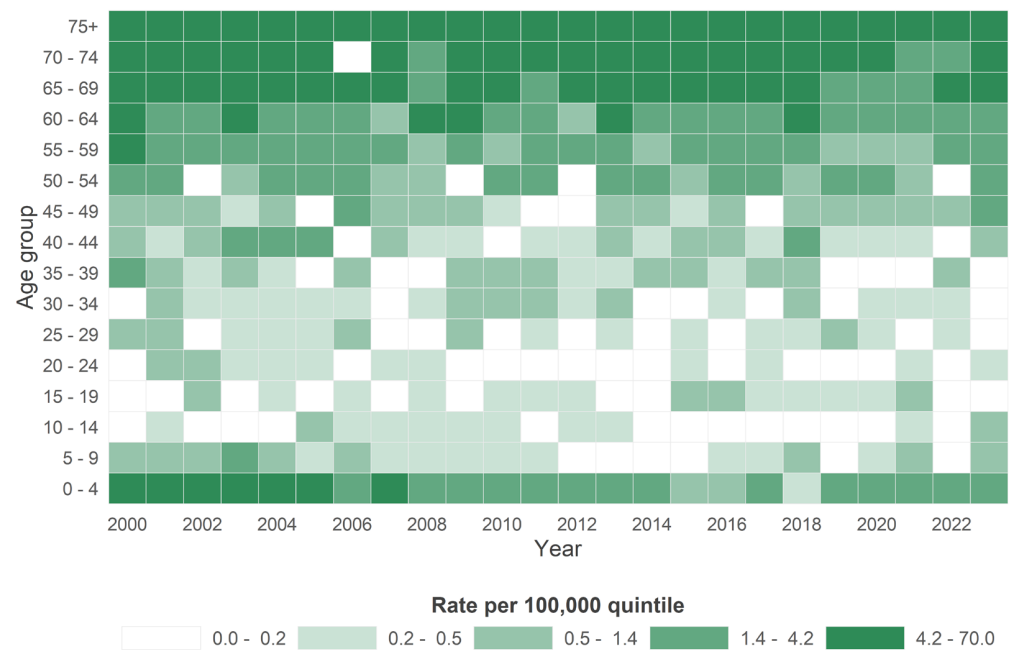


Figure 2. Annual age-specific crude mortality rates attributable to waterborne infectious diseases in Costa Rica, 2000–2023. Rates are expressed as deaths per 100,000 population within each age group and year and are classified by quintiles.

County-level variation persisted after indirect standardization by calendar year, sex, and age group. The global empirical Bayes-smoothed SMR was highest in Talamanca (1.95; 95% credible interval: 1.44–2.54), followed by Coto Brus (1.73; 1.30–2.22), Buenos Aires (1.46; 1.06–1.91), Matina (1.42; 1.00–1.91), and Limón (1.40; 1.11–1.73). Elevated relative mortality was also observed in Puntarenas (SMR: 1.34; 1.09–1.62), San José (1.31; 1.16–1.46), and Turrialba (1.29; 1.00–1.61). The smoothed county-level pattern showed that mortality above the national expected level was distributed across southern, Caribbean, Pacific, and selected Central Valley counties, rather than being confined to a single geographic region (Figure 3).

3.5. Years of Life Lost

A total of 57,625.5 years of life lost were estimated during 2000–2023 among the 2412 deaths eligible for individual YLL estimation. The mean YLL per death was 23.9 years, and the national YLL rate was 53.76 per 100,000 person-years. The 0–4 age group contributed the largest absolute premature mortality burden, accounting for 20,605.1 YLL (35.8% of total YLL), with a mean of 77.8 YLL per death and a YLL rate of 232.70 per 100,000 person-years. In contrast, the 75+ age group accounted for the largest number of deaths and contributed 8976.3 YLL, with a mean of 7.5 YLL per death and a YLL rate of 288.89 per 100,000 person-years. Thus, the YLL profile reflected a dual burden: substantial loss of life associated with deaths in early childhood and a high rate of YLL among older adults because of their markedly higher mortality frequency.

The proportional annual distribution of YLL varied across the study period. In 2000, the 0–4 age group accounted for 60.5% of annual YLL, compared with 20.5% in 2023. Over the same interval, the contribution of older age groups became more prominent, although annual composition remained variable. For example, the 75+ age group accounted for 5.8% of annual YLL in 2000 and 29.6% in 2017, when its relative contribution was highest. These patterns were descriptive and reflected variation in the age distribution of deaths over time (Figure 4).

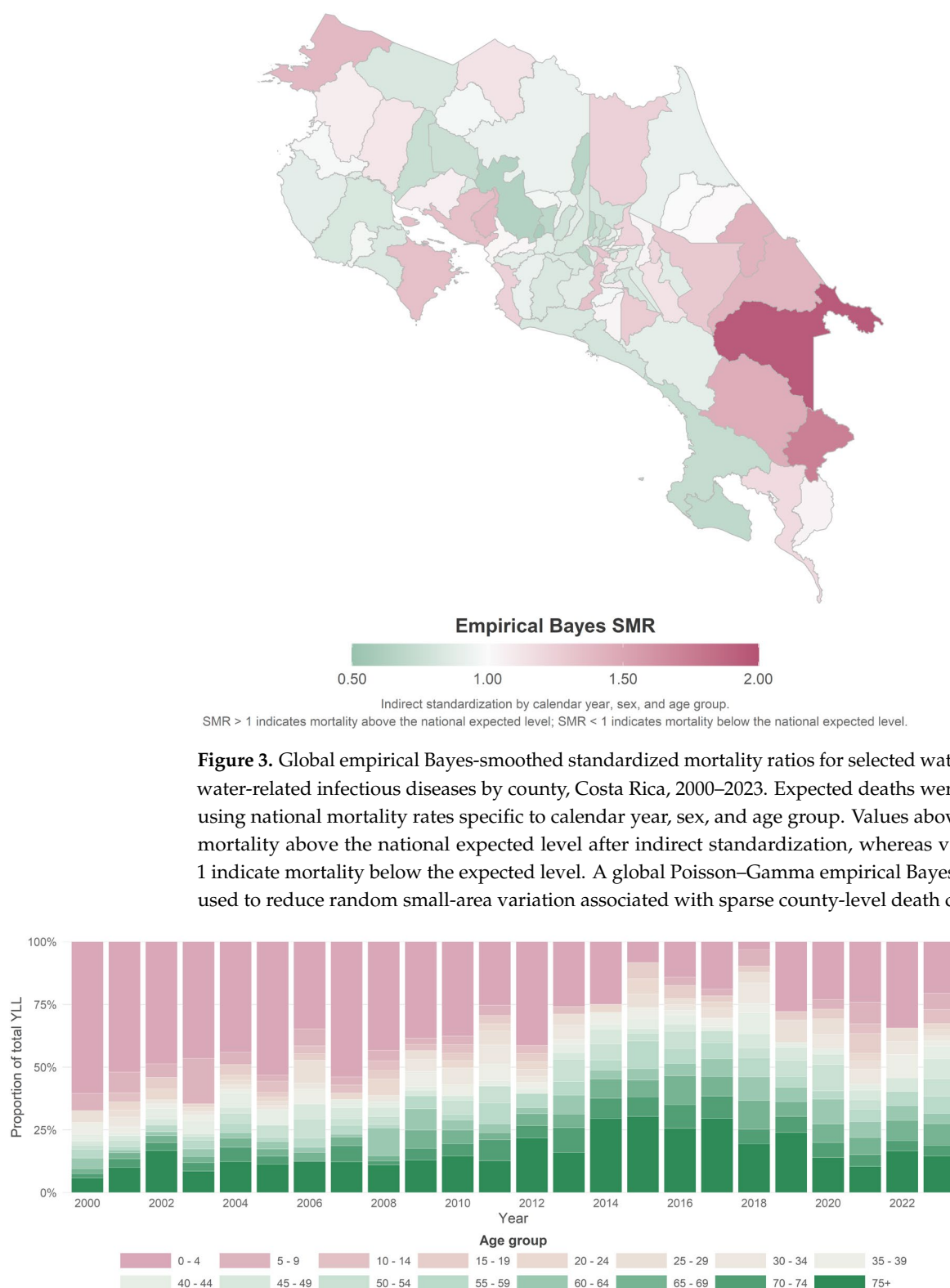


Figure 3. Global empirical Bayes-smoothed standardized mortality ratios for selected waterborne and water-related infectious diseases by county, Costa Rica, 2000–2023. Expected deaths were calculated using national mortality rates specific to calendar year, sex, and age group. Values above 1 indicate mortality above the national expected level after indirect standardization, whereas values below 1 indicate mortality below the expected level. A global Poisson–Gamma empirical Bayes model was used to reduce random small-area variation associated with sparse county-level death counts.

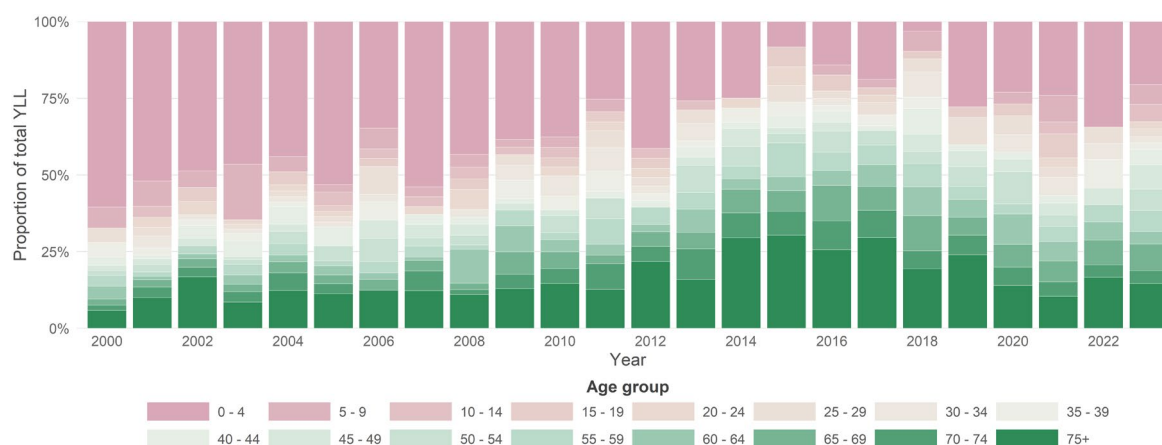


Figure 4. Annual proportional distribution of total years of life lost by age group, Costa Rica, 2000–2023. Each bar represents the percentage of annual YLL contributed by each age group.

Spatial differences in premature mortality were evident across provinces. Limón had the highest YLL rate (86.13 per 100,000 person-years), followed by Puntarenas (80.55 per 100,000 person-years) and Guanacaste (73.49 per 100,000 person-years). Although San José contributed the highest absolute number of YLL (17,030.3), its YLL rate was lower (46.14 per 100,000 person-years) because of its larger population denominator. Age-specific YLL

patterns differed across provinces. The largest early-childhood YLL rates were observed in Limón (453.97 per 100,000 person-years), Puntarenas (443.16 per 100,000 person-years), and Guanacaste (309.39 per 100,000 person-years). In these provinces, deaths among children aged 0–4 years accounted for a particularly important component of the premature mortality burden. At the same time, YLL rates among adults aged 75 years or older were substantial across all provinces, reflecting the high frequency of deaths in older populations. Overall, the provincial pattern showed that premature mortality was not limited to a single age group: the largest absolute loss of life was concentrated in early childhood, whereas high YLL rates among older adults remained a prominent component of the burden (Figure 5).

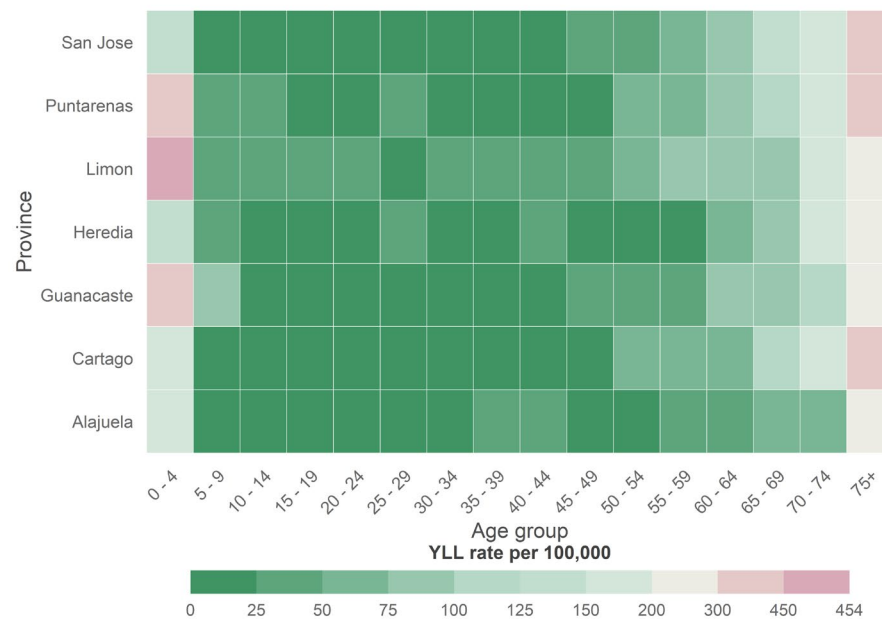


Figure 5. Years of life lost rates by province and age group, Costa Rica, 2000–2023. Rates are expressed per 100,000 person-years and were calculated using sex- and age-specific remaining life expectancy from provincial INEC life tables.

4. Discussion

This nationwide ecological study describes the mortality burden attributable to water-borne infectious diseases in Costa Rica over a 24-year period. Three main findings emerged. First, mortality was relatively low in absolute terms but persistent, with 2450 deaths between 2000 and 2023 and a burden dominated by infectious gastroenteritis, diarrhea, and other bacterial intestinal infections. Second, the age pattern was bimodal: the highest crude mortality rates were observed among older adults, especially those aged 75 years or older, but children aged 0–4 years also showed elevated crude mortality compared with most young and middle-adult groups. Third, YLL revealed a different and more policy-relevant burden profile than death counts alone; premature mortality was concentrated in early childhood and was disproportionately higher in peripheral provinces, particularly Limón, Puntarenas, and Guanacaste. These findings suggest that waterborne infectious disease mortality in Costa Rica is not only a residual infectious disease problem, but also a marker of age-specific vulnerability and territorial inequality.

The predominance of infectious gastroenteritis and diarrhea is consistent with the global burden of diarrheal diseases, which remain a major cause of preventable mortality despite substantial reductions over recent decades. The most recent Global Burden of Disease estimates reported that diarrheal diseases caused approximately 1.17 million deaths globally in 2021, with the highest mortality rates concentrated among children

under five and older adults. This age profile is consistent with the pattern observed in Costa Rica: mortality rates were highest among older adults, but early childhood remained an important component of fatal waterborne disease burden [1]. The concentration of deaths in broad categories such as infectious gastroenteritis and diarrhea also suggests that mortality statistics may capture a mixture of etiologies, including bacterial, viral, and parasitic agents, some of which may not be specified in death certification [7,35]. This reinforces the need to strengthen etiologic surveillance for severe diarrheal disease, especially in settings where mortality is relatively uncommon but still preventable [36].

The temporal pattern showed higher crude and age-standardized mortality rates during the early 2000s, a peak around 2016–2017, and lower values after 2018. This decline is compatible with long-term improvements in health services, water access, sanitation, vaccination, and case management, but it should not be interpreted as evidence that risk has been eliminated. Globally, unsafe drinking water, sanitation, and hygiene continue to explain a large share of diarrheal disease burden. A 2019 update estimated that 1.4 million deaths and 74 million DALYs could have been prevented through safe WASH, and that diarrhea represented most of the WASH-attributable burden [6]. The decline observed after 2020 should also be interpreted cautiously because the COVID-19 pandemic altered health-seeking behavior, pathogen transmission, diagnostic practices, and mortality coding for several infectious diseases [37–39]. Therefore, the lower rates in the most recent years may reflect a combination of real epidemiological change, changes in exposure, and changes in surveillance or certification [40,41]. However, recent mandatory-notification data indicate that acute diarrheal disease morbidity remains high: 487,182 cases were reported in Costa Rica in 2024, corresponding to 9175.5 cases per 100,000 population and exceeding the expected endemic channel [42]. Because these surveillance data represent notified morbidity and use a different case definition from the expanded mortality definition applied in this study, their relationship with recent mortality trends cannot yet be established and should be reassessed using harmonized and updated mortality data.

Age-specific findings are central to the interpretation of this study. The highest crude mortality rate was observed among persons aged 75 years or older, consistent with evidence that diarrhea remains an important cause of death among older adults. A recent global analysis of diarrhea in older adults reported that although mortality declined between 1990 and 2021, older adults still contributed a large number of diarrhea-related deaths, particularly in older age strata [5]. This pattern is biologically plausible because older adults are more vulnerable to dehydration, electrolyte imbalance, frailty, comorbidities, and severe outcomes following gastrointestinal infection [1,43]. However, the Costa Rican results also show that children aged 0–4 years remain a relevant mortality group. This is important because the age-specific crude mortality heatmap and the YLL results point in the same direction: the country has a dual burden in which older adults carry the highest mortality rates, while young children carry a disproportionate burden of premature mortality [7,44].

The YLL analysis was essential because it changed the interpretation of the burden. Death counts alone would emphasize older adults, particularly the 75+ age group. In contrast, YLL showed that the 0–4 age group contributed the largest share of premature mortality, with 21,168.5 YLL and a YLL rate of 239.07 per 100,000. The proportional YLL distribution also showed that children aged 0–4 years accounted for 64.7% of annual YLL in 2000, followed by a gradual redistribution of burden toward older ages. This pattern is consistent with the demographic and epidemiological transition of Costa Rica. The country has experienced population growth and aging, with the proportion of people aged 65 years or older increasing from 2000 to 2024 [45]. Therefore, the observed redistribution of YLL likely reflects both improvements in child survival and the increasing contribution of older adults to infectious disease mortality in an aging population.

Territorial differences were more evident when premature mortality was considered. Although cumulative crude mortality rates were highest in Puntarenas, San José, and Limón, YLL rates were highest in Limón (86.13 per 100,000 person-years), Puntarenas (80.55 per 100,000 person-years), and Guanacaste (73.49 per 100,000 person-years). This distinction is important because San José contributed the highest absolute number of YLL (17,030.3), reflecting its larger population denominator, whereas Limón showed the highest population-based premature mortality burden. Early-childhood YLL rates were particularly high in Limón (453.97 per 100,000 person-years), Puntarenas (443.16 per 100,000 person-years), and Guanacaste (309.39 per 100,000 person-years), indicating that mortality among children aged 0–4 years represented an important component of the burden in these provinces. These descriptive patterns are consistent with broader evidence showing that favourable national health indicators may conceal territorial and social gradients in health and mortality in Costa Rica. However, the present ecological analysis did not include individual or area-level measures of socioeconomic conditions, water quality, sanitation coverage, healthcare access, or other potential determinants; therefore, these factors should be examined in future analytical studies [21].

Although Costa Rica has broad public health-care coverage, formal coverage may not ensure timely access for all population groups. Migratory status, informal employment, and lack of insurance can create barriers to care, particularly among migrants in irregular situations [46]. Evidence from Latin America also suggests that childhood diarrheal mortality may reflect both barriers to access and delays or deficiencies in primary care [47]. These factors could contribute to the age and territorial patterns observed in this study. However, this interpretation remains hypothesis-generating because the mortality records did not include insurance status, migratory status, health-service utilization, or treatment received.

Furthermore, the geographic concentration of YLL in peripheral and coastal provinces may reflect multiple mechanisms, including differences in water quality, sanitation infrastructure, rurality, access to timely care, environmental exposure, and social vulnerability [48]. This interpretation should remain cautious because the present study did not include individual-level socioeconomic, ethnic, household water, or sanitation variables. However, previous Latin American evidence supports the link between waterborne disease burden and structural vulnerability [49]. A national study in Ecuador found higher morbidity and mortality due to waterborne diseases among Indigenous populations, as well as higher burden among young children and older adults [49]. In Costa Rica, some of the provinces with higher YLL also include historically marginalized territories and Indigenous populations; therefore, the observed pattern should be interpreted as a hypothesis-generating signal of environmental and social inequity, not as direct evidence of individual-level causation [20,50].

These findings also suggest that high national water coverage does not necessarily eliminate residual risk. Costa Rica has achieved important progress in drinking-water supply, but local vulnerabilities remain relevant, especially in small and community-managed systems [17]. Studies of small drinking-water systems in Costa Rica have reported the occurrence of pathogenic microorganisms and fecal contamination indicators, including rotavirus, somatic coliphages, fecal coliforms, and *Escherichia coli*, in samples from ASADAS, Administrative Associations of Rural Aqueduct and Sewer Systems (ASADAS, from the Spanish Asociaciones Administradoras de Sistemas de Acueductos y Alcantarillados Sanitarios) [18]. Recent work on surface water quality in Costa Rica has also emphasized ongoing challenges related to water quality, wastewater treatment, and sanitation policy [51]. This is relevant for interpreting the present results, given the burden observed here may represent the severe end of a broader exposure continuum in which failures in

water safety, sanitation, and environmental contamination translate into fatal outcomes among the most vulnerable age groups.

Leptospirosis represented a smaller but important component of mortality, accounting for 7.0% of deaths. Its inclusion broadens the interpretation from a narrow diarrheal-disease framework to a One Health perspective [52,53]. Unlike classical diarrheal infections, leptospirosis is a zoonotic and environmentally mediated disease associated with animal reservoirs, contaminated water or soil, rainfall, flooding, occupational exposure, and inadequate sanitation. Costa Rican evidence has described leptospirosis as an endemic and increasing disease, while recent international evidence continues to associate leptospirosis with rainfall, flooding, environmental exposure, and occupational risk [54]. Thus, the mortality burden described in this study likely reflects both drinking-water and sanitation-related pathways and broader environmental transmission pathways involving water, animals, land use, and climate-sensitive exposures.

The public health implication is that surveillance should move beyond national averages and crude death counts. If only absolute deaths are considered, densely populated areas such as San José dominate the burden. If crude rates are considered, some provincial differences emerge. However, when YLL is included, peripheral provinces and early childhood mortality become much more visible. This supports the value of incorporating premature mortality metrics into environmental health surveillance [22]. YLL can help identify territories where deaths occur earlier, not merely where deaths are more numerous. In practical terms, this suggests that interventions should prioritize severe diarrheal disease surveillance in young children, protection of older adults against dehydration and complications, microbiological monitoring of small water systems, improved wastewater management, and integrated One Health surveillance for leptospirosis and other environmentally mediated infections [52,55,56].

This study has limitations. Because the design was ecological, associations were interpreted at the population level, and no individual-level causal inference was attempted [24]. Death certificate data may be affected by misclassification of the underlying cause of death, especially for broad categories such as infectious gastroenteritis and diarrhea. Despite these limitations, the study used national mortality and population records over 24 years, applied age-standardization, incorporated YLL, and combined temporal, demographic, and spatial analyses to describe a preventable mortality burden that would be underestimated by crude counts alone.

5. Conclusions

Mortality classified under selected ICD-10 codes for waterborne, water-related, and foodborne infectious diseases in Costa Rica was relatively low but persistent during 2000–2023. The burden was dominated by diarrheal and other bacterial intestinal infection categories, indicating that preventable enteric and sanitation-related conditions remain relevant despite high national drinking-water coverage. Mortality showed a bi-modal demographic pattern, with the highest crude mortality rates among older adults and a relevant early-childhood component. However, YLL revealed a distinct burden profile: the largest premature mortality burden occurred among children aged 0–4 years, while provincial YLL rates were highest in Limón, Puntarenas, and Guanacaste. These findings show that crude death counts alone underestimate the public health relevance of these conditions. Surveillance and prevention strategies should incorporate age-standardized rates, premature mortality metrics, and territorial analyses to identify vulnerable populations and guide actions in water safety, sanitation, etiologic surveillance, and environmental health. Future studies should integrate mortality data with morbidity surveillance, water-quality monitoring, sanitation coverage, indicators of infrastructure development, socioeconomic

conditions, and climate-related exposures, including seasonal variation, to better identify the drivers of long-term and territorial inequalities and inform context-specific prevention and surveillance strategies across regions.

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Abbreviations

The following abbreviations are used in this manuscript:

ASADAS	Asociaciones Administradoras de Sistemas de Acueductos y Alcantarillados Sanitarios
ASMR	Age-standardized mortality rate
DALY	Disability-adjusted life year
ENSO	El Niño–Southern Oscillation
GAM	Greater Metropolitan Area
GBD	Global Burden of Disease
ICD-10	International Classification of Diseases, 10th Revision
INEC	Instituto Nacional de Estadística y Censos
IQR	Interquartile range
LMICs	Low- and middle-income countries
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
WASH	Water, sanitation, and hygiene
YLL	Years of life lost

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