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Original article

Long-Term Patterns of Groundwater E. coli Contamination in Tripoli and Souq al-Jomaa, Libya (1990–1995): Seasonal Variability, Rainfall Influence, and Public Health Implications

Khairi Alennabi*[1], Ennajh Rahel[2], Aymin Almiqrhi[3], Tarek Abukreba[3], Ali Aldrhoubi[4]

[1]*Department of Plant Tissue Culture. Libyan Center for Biotechnology, Tripoli, Libya.*
[2]*Department of Environmental Safety Technologies, Higher Institute for Occupational Safety and Health Technologies, Al-Sabi'ah, Libya*
[3]*Department of Environment, Food and Biological Applications. Libyan Center for Biotechnology, Tripoli, Libya.*
[4]*Department of Strategic Research on Health, Environmental, and Food Security, Center for Strategies and International Research and Studies, Sidi Sayeeh. Libya*
Email. *Kan_sy1971@yahoo.com*

Abstract
Domestic water supply in Libya and many other arid and semi-arid regions is primarily from groundwater. This study assessed historical trends of Escherichia coli (E. coli) contamination in private wells in Tripoli and Souq al-Jomaa, Libya, and their relationship with seasonal rainfall variability and reported waterborne disease cases for the period 1990–1995. Methods: A retrospective observational study was conducted using archival records from the Ras Hassan Water Laboratory, which included microbiological analyses of 2,428 wells (1,230 in Tripoli and 1,198 in Souq al-Jomaa). Annual contamination prevalence and monthly contamination percentages were derived from routine laboratory testing for E. coli using membrane filtration techniques (0.45 µm cellulose ester, 100 mL, m-FC agar, 44.5 °C for 24 hours). The rainfall data were obtained from the National Meteorological Center, and the waterborne disease data were collected from hospital archives. Seasonal comparisons were performed using repeated-measures ANOVA, the correlation between rainfall and contamination was calculated using Pearson's correlation, and temporal trends were assessed using the Mann-Kendall test. Results: In Tripoli, the six-year average E. coli prevalence was 70.4% compared to 56.5% in Souq al-Jomaa (Mann-Whitney U test, $p<0.01$). Monthly contamination was highest in winter (Dec–Feb: 79% in Tripoli, 71% in Souq al-Jomaa) and lowest in summer (66% and 44%, respectively). Annual rainfall was variable, ranging from 420 mm in 1990 (highest) to 240–280 mm in 1994–1995 (lowest), with intermediate values in 1992–1993 (~330 mm). Monthly rainfall was strongly correlated with contamination in Souq al-Jomaa ($r = 0.78$, $p < 0.01$) and moderately in Tripoli ($r = 0.52$, $p < 0.05$). Peak contamination occurred during the wettest months (Dec–Jan, 60–90mm). A total of 1,748 cases of waterborne diseases were reported, with the highest incidence in 1994 (431 cases). Females represented 62% of cases. No significant temporal trend was detected for contamination or disease, but the six-year limit statistical power. Conclusion: Rainfall appears to be an important contributor to seasonal E. coli contamination in shallow wells, especially in shallower aquifers (Souq al-Jomaa). The observed temporal patterns suggest a need for pre-winter well protection and disinfection.
Keywords. *E. coli*, Groundwater Contamination, Membrane Filtration, Rainfall.

Introduction
Groundwater is a vital component of the global water supply, providing drinking water for billions of people worldwide [1-3]. Arid and semi-arid zones have limited and seasonal surface water resources and are largely dependent on groundwater as their main source of water for domestic, agricultural, and industrial purposes [4, 5]. Groundwater has often been protected from the effects of surface contamination. However, rapid urbanization, ever-increasing populations, poor sanitation infrastructures, and unrestricted land use practices have made groundwater vulnerable to pathogen contamination [6, 7]. Microbial contamination of groundwater is a serious threat to public health as it is related to infectious diseases such as enteric diseases [8,9]. Among the variety of microbial indicators, Escherichia coli is often cited as the most effective and reliable indicator of fecal contamination in water and, thus, is commonly used in drinking water monitoring activities [10,11]. If E. coli is detected in the groundwater, there is a high probability that other pathogenic microorganisms are also present due to fecal pollution of water sources [12,13]. Many research works have shown the effect of hydrogeological conditions, precipitation, quality of well design, distance to sanitation structures, and land use on groundwater contamination [14]. Precipitation becomes particularly significant because it enhances groundwater recharge, facilitates contamination of the soil surface by mobilizing the contaminants, and promotes rapid migration of microorganisms from the surface down to the shallow aquifer [15]. As a result, distinct seasonal changes occur in the microbial composition of groundwater, where contamination rates increase in rainy periods [16,17].
Libya is considered one of the most stressed countries in the world regarding water supplies. It has to resort to groundwater because of its arid climate. As a result of the limited availability of freshwater from perennial rivers, Libya depends heavily on local and regional aquifers in addition to privately drilled wells [18]. Shallow private wells remain an important source of drinking water in the cities near Tripoli despite the growing stress caused by urbanization and dilapidation of sanitation services [19]. During the study period, the

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Tripoli Metropolitan Region has witnessed significant development in terms of demographic changes and infrastructure. Urban growth means more wastewater, and sewage systems leak, and the use of septic tanks increases the likelihood of shallow groundwater contamination with microbes [20]. This is especially the case when the water table is shallow, and wellheads are not protected [21-23]. The chemistry of groundwater in Libya has been widely studied, but there have not been many detailed studies on microbial water pollution [24,25,26]. The available data cover only short time periods, small areas, or annual patterns. Thus, we know little about how seasonal changes affect contamination and related health risks [27,28].

One important issue of concern with regard to the extant literature is that there is no readily available dataset that comprises groundwater microbiology data, meteorology, and information on the health status of people living in this area. Such information is necessary for establishing whether patterns of contamination are stable and whether they have any seasonal characteristics that might be correlated with the risk of waterborne diseases. The importance of the current study stems from the fact that it examines a six-year history of groundwater contamination in Tripoli and Souq al Jomaa by integrating microbiology information collected in the laboratory, precipitation rates, and information on the prevalence of illnesses among residents.

This study draws upon archival data from the Ras Hassan Water Laboratory (Government Water Analysis Center) covering the years 1990 to 1995. The dataset includes detailed annual well records, monthly contamination percentages, rainfall data obtained from the National Meteorological Center, and hospital records documenting waterborne diseases. The research was designed with several objectives in mind. First, it aimed to compare the prevalence and seasonality of E. coli contamination in Tripoli and Souq al Jomaa. Second, it sought to determine the relationship between seasonal contamination patterns and rainfall. Third, it evaluated the dependence of well depth on sensitivity to contamination. Fourth, it assessed temporal trends across the six-year study period. Finally, it quantified the number of waterborne disease cases recorded during the study timeframe.

Methods

Study area

The study took place in two districts of the Greater Tripoli region in northwestern Libya: Tripoli and Souq al Jomaa. Tripoli, the capital and largest city in Libya, has a very dense population and many residential buildings. The infrastructure is relatively old, and there is growing pressure on the sanitation systems. On the other hand, Souq al Jomaa is a mix of residential areas and peri-urban zones with more open spaces and farming activities. The area has a Mediterranean semi-arid climate, with mild wet winters and long hot dry summers. Most of the rain falls between November and March. Summers are essentially dry. This climate allows researchers to investigate how the seasons affect groundwater microbial contamination.

Study design and data sources

This study employed a retrospective observational design based on archival records collected between January 1990 and December 1995. Historical datasets were obtained from three primary sources:

1. Water quality data: Ras Hassan Water Laboratory. Citizens who had drilled or owned wells submitted individual water samples for potability testing. This citizen-initiated sampling constitutes a convenience sample, which may overrepresent wells with suspected contamination. Each well was sampled once (cross-sectional design). The laboratory recorded the date, location, well depth (as reported by the owner), and the microbiological result. A total of 2,428 wells were studied (Tripoli: 1,230; Souq al Jomaa: 1,198).
2. Rainfall data: National Meteorological Center of Libya. Monthly and annual rainfall data were obtained from the Tripoli meteorological station.
3. Health data: Reported cases of waterborne diseases from the hospital archives of the Infectious Diseases Department of Tripoli Central Hospital. The integration of environmental and health datasets enabled examination of temporal patterns in groundwater contamination and their potential association with rainfall variability and disease occurrence.

Microbiological analysis

Microbiological analyses were performed at the Ras Hassan Water Laboratory according to standard water quality testing procedures in use during the study period.

Target organism: Escherichia coli (fecal coliforms).

Method: Membrane filtration (APHA, 2012).

•Filter membrane: Cellulose esters, 0.45 µm pore size, 47 mm diameter.
•Sample volume: 100 mL.
•*Culture medium: m FC agar (Difco).*
•Incubation: 44.5 ± 0.2 °C for 24 ± 2 hours.
•Enumeration: Blue colonies were counted as E. coli and reported as colony-forming units per 100 mL (CFU/100 mL). Wells were classified as contaminated when at least one E. coli colony was detected per 100 mL sample.

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Two types of data were extracted:

Annual well classification (prevalence data)
For each year and area, the laboratory provided the total number of wells tested, the number with no detectable E. coli (0 CFU/100 mL), and the number with E. coli detected (≥1 CFU/100 mL). Annual contamination prevalence (%) = (contaminated wells / total wells) × 100.

Monthly contamination percentages (intensity data)
The monthly contamination percentage (0–100%) was calculated as the proportion of individual well samples testing positive for E. coli within that calendar month. For example, if 8 out of 10 wells tested in a given month showed detectable E. coli, the monthly contamination percentage would be 80%. These values were derived from the original Excel spreadsheet (1990–1995) and are presented in Figures 1a–1f.

Well depth data
Well depth was reported by owners and not independently verified. The aggregated data are:
•Tripoli: Mean 22 m (range 20–25 m).
•Souq al Jomaa: Mean 14 m (range 13–16 m).
Because only area-averaged depths are available, the analysis of depth contamination sensitivity is limited to a qualitative comparison between the two areas.

Rainfall data
Monthly and annual rainfall data (1990–1995) were obtained from the Tripoli meteorological station (National Meteorological Center). Key features:
•Winter (Dec–Jan): 60–90 mm/month.
•Autumn/spring (Nov, Feb): 30–50 mm/month.
•Summer: near zero.
•Annual totals: 1990 (420 mm); 1992–1993 (~330 mm); 1994–1995 (240–280 mm).

Waterborne disease data
Hospital records from the Infectious Diseases Department of Tripoli Central Hospital were reviewed for 1990–1995. Cases diagnosed as waterborne infections (gastroenteritis, typhoid, hepatitis A, etc.) were extracted, stratified by year and sex. Diagnostic criteria were not standardized; thus, the 1,748 cases represent a minimum estimate.

Seasonal classification
Based on the Mediterranean climate:
•Winter (DJF): December, January, February.
•Spring (MAM): March, April, May.
•Summer (JJA): June, July, August.
•Autumn (SON): September, October, November.

Statistical analysis
Analyses were conducted using Python packages including SciPy, StatsModels, and pyMannKendall. Annual prevalence was compared using the Mann–Whitney U test, a non-parametric method chosen because of the small sample size of six annual values per area. Seasonal differences in contamination intensity were examined with repeated measures ANOVA, treating month as the repeated factor across seventy-two monthly observations per area, with the calendar month aggregated across years serving as the subject. The relationship between rainfall and contamination was assessed through Pearson correlation applied to seventy-two monthly rainfall–contamination pairs. Temporal trends in annual prevalence were tested using the Mann–Kendall procedure, again based on six values per area. A significance threshold of $\alpha = 0.05$ was applied throughout, and results were interpreted conservatively in recognition of the observational design and limited annual sample size.

Results
A total of 2,428 groundwater samples collected between 1990 and 1995 were analyzed to assess temporal patterns of microbial contamination. The results are presented at annual, monthly, and seasonal scales and are further examined in relation to rainfall variability and reported waterborne disease.

Annual E. coli contamination prevalence
(Table 1) presents the annual contamination prevalence. Over six years, the average prevalence in Tripoli was 70.4% (range 64.0–77.8%), compared to 56.5% (range 48.8–65.7%) in Souq al-Jomaa. The difference was statistically significant (Mann-Whitney U = 0, $p < 0.01$).

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Table 1. This is a table. Tables should be placed in the main text near the first time they are cited

Year	Tripoli Wells (n)	Tripoli Contaminated (n)	Tripoli Prevalence (%)	Souq al-Jomaa Wells (n)	Souq al-Jomaa Contaminated (n)	Souq al-Jomaa Prevalence (%)
1990	172	110	64.0	91	48	52.7
1991	118	83	70.3	123	60	48.8
1992	119	85	71.4	134	68	50.7
1993	349	264	75.6	116	68	58.6
1994	108	84	77.8	117	73	62.4
1995	244	154	63.11	175	115	65.7
Mean	–	–	70.0	–	–	56.5

Monthly contamination percentages and seasonal intensity

Monthly contamination percentages were also evaluated throughout the study period to assess temporal fluctuation in groundwater microbial quality. The monthly analysis provides a better understanding of the dynamics of contamination than annual averages alone, allowing to distinguish seasonal fluctuations and short-term variations. In regions with strong climatic seasonality, where distributions of rainfall and environmental conditions may be influential for transport and persistence of fecal contaminants in groundwater systems, monthly evaluations of patterns of contamination are particularly important. Therefore, monthly contamination records from Tripoli and Souq al Jomaa were analyzed to assess seasonal intensity, identify periods of elevated contamination risk, and compare temporal patterns between the two study areas. Figures 1a–1f show the monthly contamination percentages for Tripoli (red lines) and Souq al Jomaa (blue lines) for each year. The detailed descriptions below follow each figure.

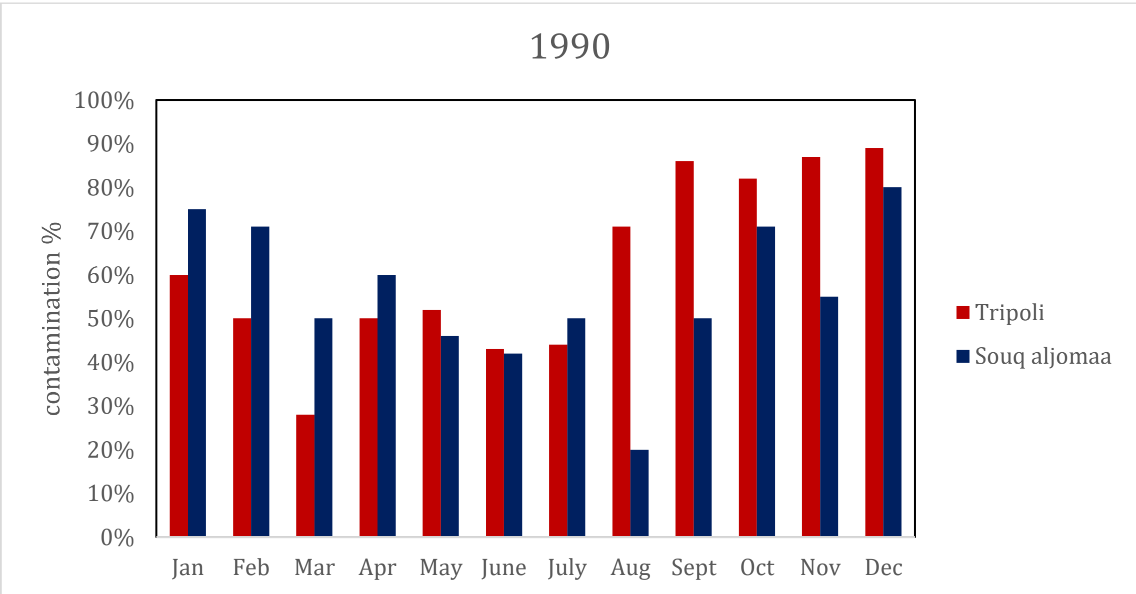

Figure 1a. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1990)

In 1990, Tripoli contamination started at 60% in January, decreased to a minimum of 28% in March, and peaked at 89% in December, with secondary peaks in September (86%) and November (87%). Souq al Jomaa ranged from a minimum of 20% in August to a maximum of 80% in December, with a marked summer decline (July 50%, August 20%). Both areas peaked in December, and Souq al Jomaa's more pronounced summer reduction is consistent with its shallower well depth.

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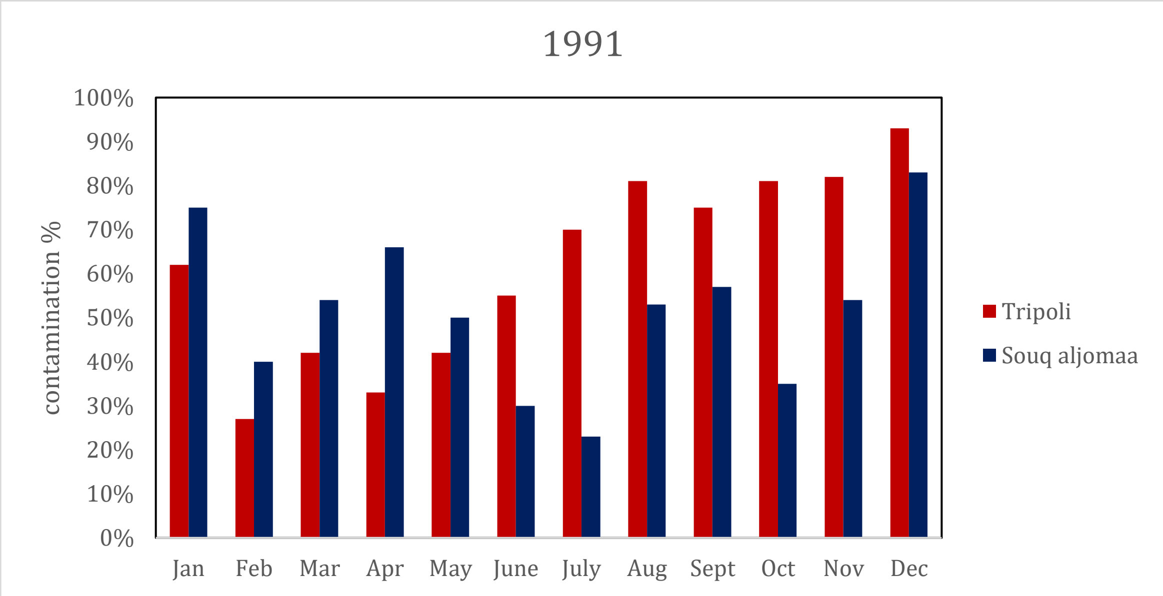

Figure 1b. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1991)

The highest E. coli contamination percentages were recorded in December in both Tripoli (93%) and Souq al Jomaa (83%), whereas the lowest values occurred in February (27%) and July (23%), respectively. Tripoli generally exhibited higher contamination levels throughout the second half of the year, indicating a greater degree of persistent groundwater vulnerability. The coincident winter peaks observed in both locations suggest a seasonal influence on groundwater microbial quality, potentially associated with increased precipitation and enhanced contaminant transport processes.

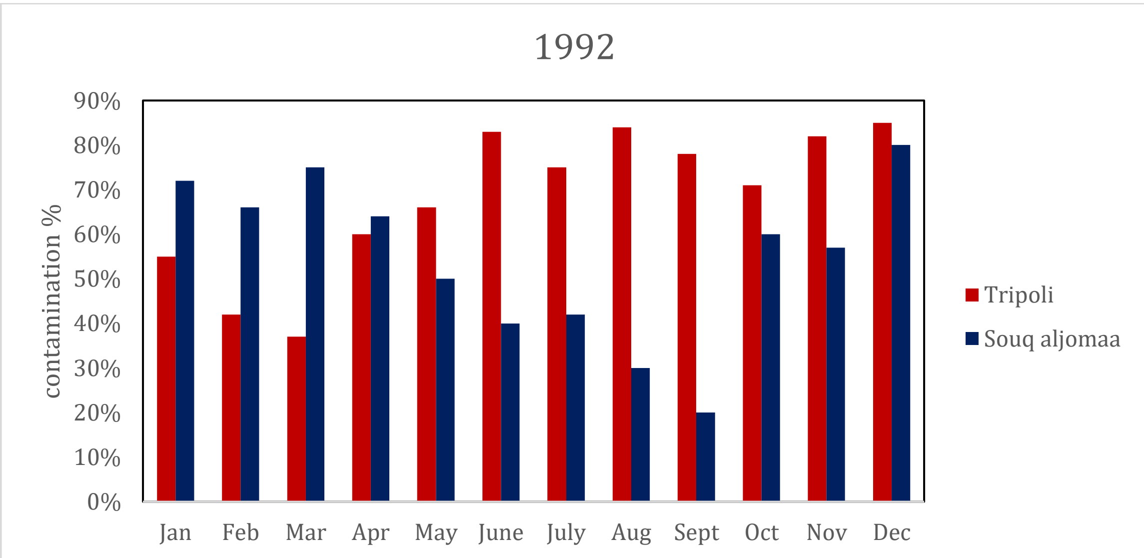

Figure 1c. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1992)

The highest E. coli contamination percentages were recorded in December in both Tripoli (85%) and Souq al Jomaa (80%), whereas the lowest values occurred in March (37%) and September (20%), respectively. The consistently higher contamination levels observed in Tripoli throughout most of the year indicate a greater degree of chronic groundwater vulnerability compared with Souq al Jomaa. The pronounced increase in contamination during the winter months further suggests the influence of seasonal environmental factors on groundwater microbial quality.

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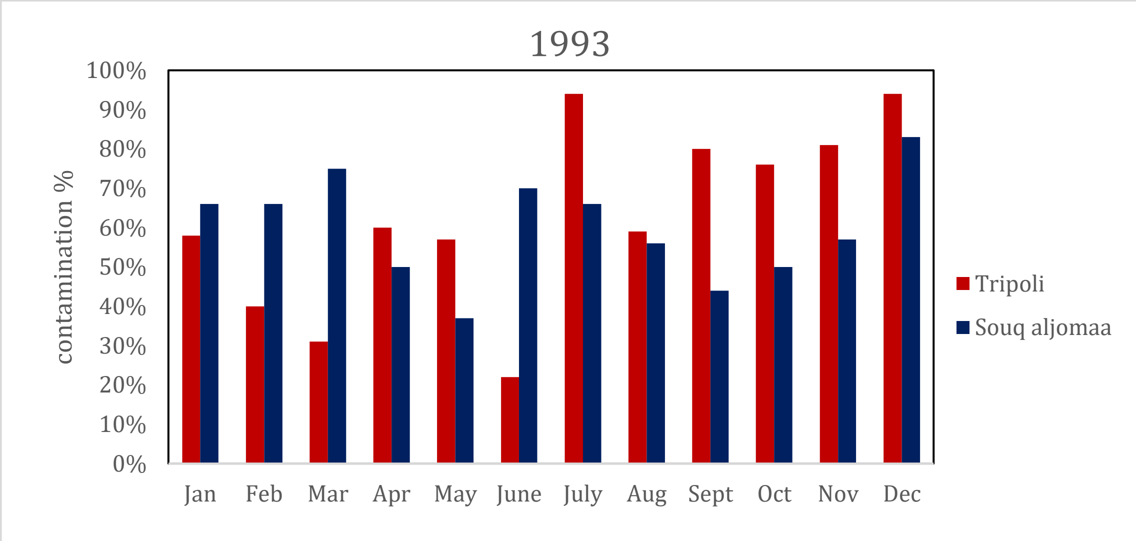

Figure 1d. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1993)

The highest E. coli contamination percentages were recorded in July and December (94%) in Tripoli and in December (83%) in Souq al Jomaa, whereas the lowest values occurred in June (22%) and May (37%), respectively. Tripoli displayed more pronounced fluctuations and higher contamination peaks throughout the year, suggesting greater susceptibility to microbial groundwater contamination. The convergence of contamination maxima during December in both study areas highlights the potential influence of seasonal environmental conditions on groundwater quality.

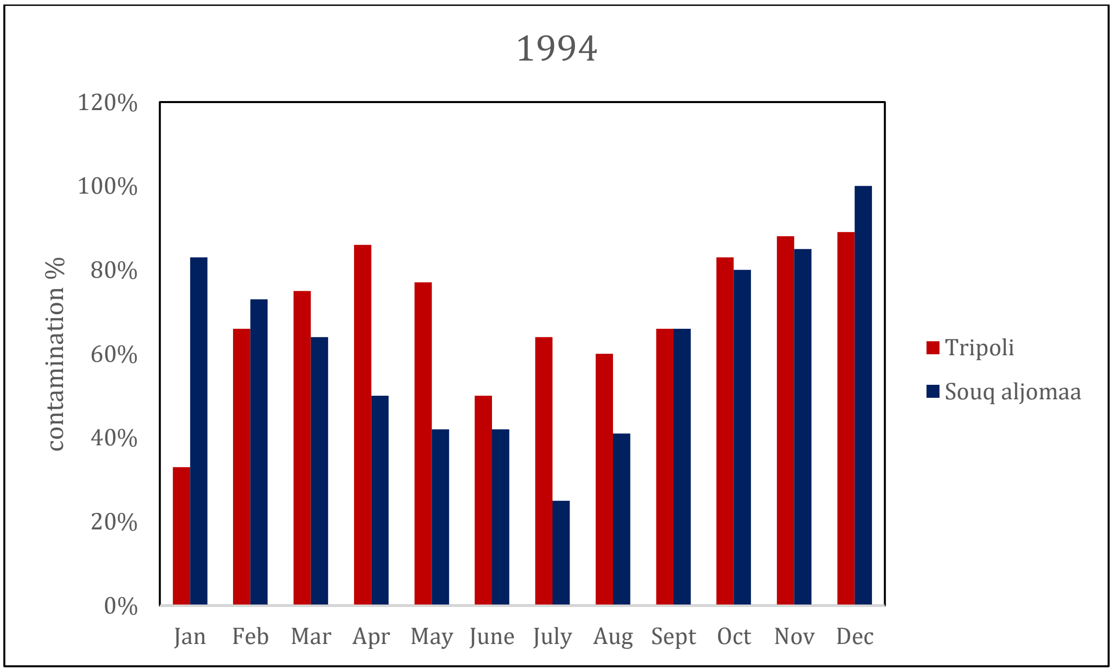

Figure 1e. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1994)

The bar graph shows the monthly percentage of contamination in Tripoli and Souq al Jomaa in 1994. When comparing the peak contamination levels for each region, distinct seasonal trends appear. The maximum contamination level for Souq al Jomaa was recorded in December, with values reaching a complete 100%, the absolute highest single data point for either region during the whole year. There is also a second, slightly lower, peak earlier in the year, in January, at approximately 83%. On the other hand, the maximum value of contamination recorded in Tripoli was in December, with about 89%. Unlike Tripoli, Souq al Jomaa did not have another major, almost identical peak earlier in the year, in April, when contamination levels were recorded at around 86%.

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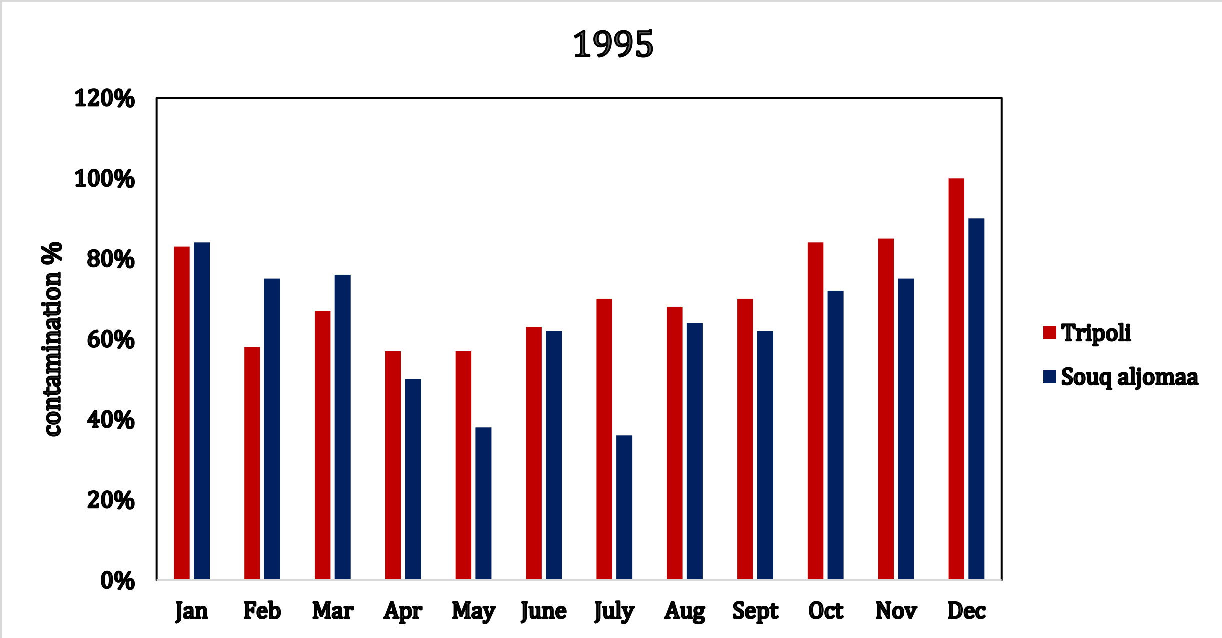

Figure 1f. Monthly E. coli contamination percentages in Tripoli and Souq al Jomaa (1995)

The comparative bar chart clearly shows the monthly changes in water contamination levels for the two areas studied in 1995. The highest rate of microbiological contamination was recorded in December in Tripoli, where the level of pollution showed its absolute annual peak at 100%. This is the maximum contamination index in the observed time interval. Tripoli also showed sustained high levels of contamination towards the end of the third and fourth quarters, with secondary peaks evident in October (84%) and November (85%), and a high baseline in January (83%). The maximum contamination value of Souq al Jomaa was observed in two different periods, showing a bimodal peak trend. The main annual peak was 90% in December; It was closely contested by the secondary winter peak in January, with a contamination rate of 84%. In general, both regions had their highest yearly pollution levels at the same time in December 1995, with Tripoli having the highest absolute level of contamination (100%) relative to Souq al Jomaa (90%). The synchronous surge is a strong indication of a common seasonal driver. For example, increased winter rainfall can initiate runoff and leaching of groundwater.

Table 2. Seasonal mean contamination percentage (%) for Tripoli and Souq al Jomaa (1990–1995)

Season	**Tripoli (mean ± SD)**	**Souq al-Jomaa (mean ± SD)**
Winter (Dec–Feb)	79 ± 10	71 ± 12
Spring (Mar–May)	72 ± 11	53 ± 14
Summer (Jun–Aug)	66 ± 13	44 ± 15
Autumn (Sep–Nov)	74 ± 9	55 ± 13

The seasonal analysis showed a clear temporal variation in the groundwater contamination for both study areas. The highest contamination levels were observed in the winter in Tripoli (79 ± 10%) and Souq al Jomaa (71 ± 12%), whereas the lowest levels were observed during the summer (66 ± 13% and 44 ± 15%, respectively). Tripoli continued to experience consistently high levels of contamination throughout the year, while the decline in Souq al Jomaa was more pronounced on a seasonal basis. Repeated measures ANOVA showed significant seasonal effects in both locations (Tripoli: $F_{(3,140)} = 5.68$, $p = 0.001$; Souq al Jomaa: $F_{(3,140)} = 12.34$, $p < 0.001$). Post hoc Tukey's HSD tests indicated that contamination values for winter were significantly higher than for summer in both areas ($p < 0.01$). Even though Souq al Jomaa has a lower prevalence of contamination, it has a greater difference between winter and summer seasons (27 percentage points) than Tripoli (13 percentage points).

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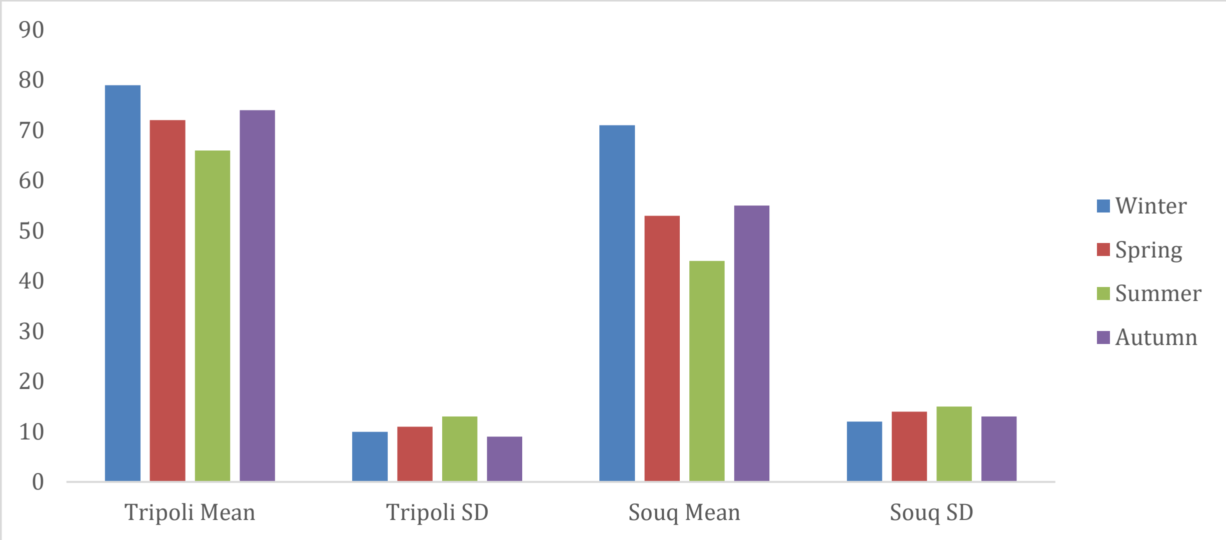

Figure 2. Seasonal mean E. coli contamination percentages (± standard deviation) for Tripoli and Souq al Jomaa (1990–1995)

The figure shows a clear seasonal pattern of groundwater contamination in both areas. Tripoli has had a persistent worrying level of contamination throughout the year, with seasonal averages not less than 65%. The maximum average contamination was observed in winter (max 79%), followed by autumn (74%) and spring (72%). The lowest average contamination index was found during the summer months (66%). Tripoli's standard deviation was between 9% and 13%, showing moderate spatial and temporal dispersion. On the contrary, Souq al Jomaa showed more seasonal variation. The highest average contamination value was observed in winter, around 71%, and then dropped markedly to the lowest annual level of 44% in the dry summer. Spring and autumn were transition periods, with spring averaging 53% and autumn 55%. The lowest average contamination level was recorded in summer in Souq al Jomaa, but also the highest standard deviation (around 15%), indicating a large inter-year variability in the dry season.

Rainfall patterns and correlation with contamination

(Table 3) shows annual rainfall totals. (Table 4) shows the average monthly rainfall.

Table 3. Annual rainfall at Tripoli station (1990–1995).

Year	Rainfall (mm)	Meteorological Characterization
1990	420	Exceptionally high
1991	~380	Above average
1992	~330	Near average
1993	~330	Near average
1994	240–280	Below average
1995	240–280	Below average

The interannual climatic variability during the period of study (1990-1995) is shown in (Table 3). The meteorological data show significant differences in the annual precipitation levels, divided into three different climatic phases. The first phase of the study was typified by high rainfall volumes with an extraordinary annual rainfall of 420mm in 1990, followed by above-average rainfall of about 380mm in 1991. This was followed by a period of stabilization throughout 1992 and 1993, with precipitation levels around the historical average of 330 mm per annum. In contrast, the last phase of the monitoring period (19941995) was characterized by a distinct change to drier conditions with annual rainfall below average, ranging between 240 and 280 mm. There is a compelling environmental correlation when cross-referencing the microbiological contamination rates with the meteorological baseline (Figure 3). The fact that the concentration of pollution peaks exclusively within the winter months (e.g., 100% in December) despite the years being classified as below average rainfall years (240-280 mm) indicates that even within the context of reduced annual precipitation regimes, sporadic first flush winter rainfall events are highly effective in flushing accumulated surface pathogens into the localized shallow aquifer.

Table 4. Average monthly rainfall (mm) for Tripoli (1990–1995)

Month	Rainfall	Month	Rainfall
Jan	75	Jul	0
Feb	50	Aug	0
Mar	30	Sep	5

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Apr	15	Oct	20
May	5	Nov	40
Jun	0	Dec	80

Correlation analysis
Souq al Jomaa contamination vs. monthly rainfall: r = 0.78, $p < 0.01$. Tripoli contamination vs. monthly rainfall: r = 0.52, $p < 0.05$.

The monthly distribution of precipitation in the study area exhibits a highly pronounced Mediterranean seasonal pattern, as summarized in (Table 4). The hydrological year is sharply divided into a humid winter period and an arid summer period. The month of December receives the highest rainfall volume of 80 mm, followed by January with 75 mm and February with 50 mm. Transitional precipitation decreases throughout the spring, with values dropping from 30 mm in March to 15 mm in April, reaching a minimum of 5 mm in May. In the summer season, the complete hyper-arid conditions are observed with no precipitation recorded from June to August (0 mm) on consecutive days. In autumn, rainfall starts again with a minimum onset in September (5 mm), followed by a progressive incremental increase in October (20 mm) and November (40 mm), bringing back the winter recharge cycle. A critical synthesis of the monthly profile of meteorological (Table 4) and the microbiological results highlights an undeniable hydrogeological link. The absolute peaks in well water contamination, regularly observed in December and January in both regions (e.g., 100% in Tripoli and 90% in Souq al Jomaa in 1995), are in close agreement with the maximum monthly rainfall volumes (80 mm and 75 mm, respectively). The synchronized occurrence of heavy precipitation events occurring throughout the winter months indicates that these events are the main environmental factors causing groundwater pollution. Heavy precipitation creates rapid infilling of both reservoirs and flooding over large areas, creating an aggregate percolation process that transports pathogens at the surface of the soil and human waste discharge located along the margins of the immediate water table to the shallow water table. On the other hand, no precipitation to very little precipitation during the months of June, July, and August greatly restricts the hydraulic transport, explaining the decrease in the average contamination values during the summer months.

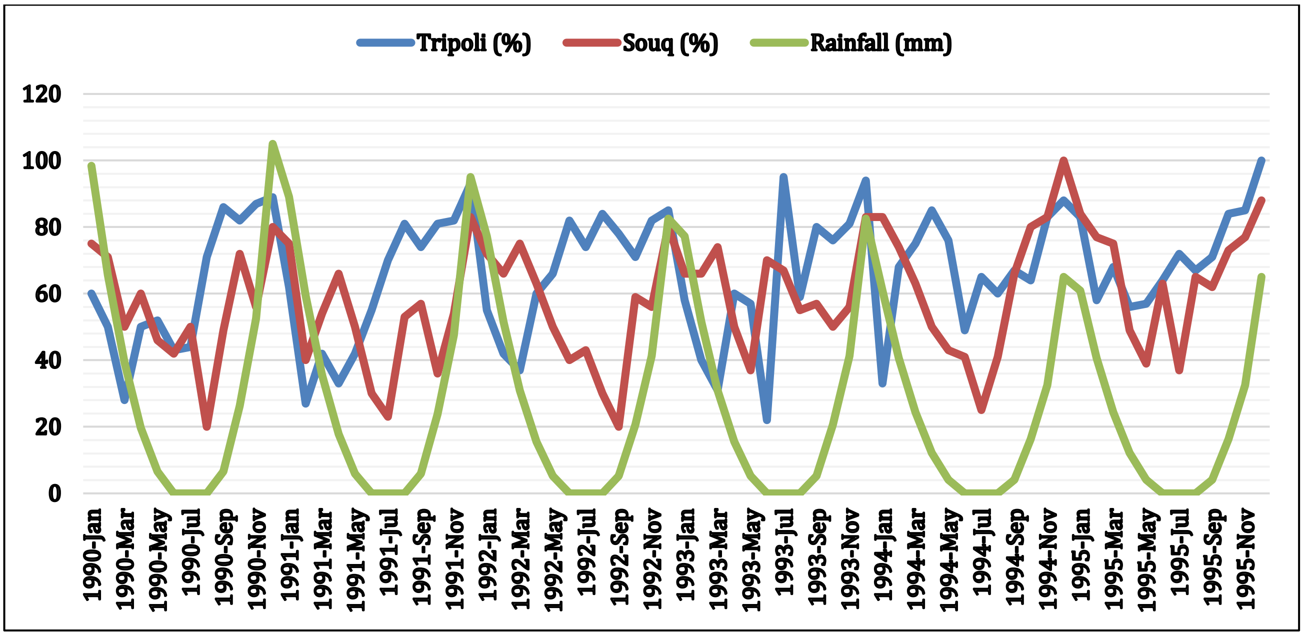

Figure 3. Monthly E. coli contamination percentages for Tripoli and Souq al Jomaa compared with estimated monthly rainfall (mm) over the study period (1990–1995)

There is also a strong seasonal pattern to rainfall, where the largest amounts occur in December and January (60-105 mm), followed by February and November (30-60 mm), and then almost none occurs between June and August. The highest levels of bacterial contamination occur during December, January, and February when it rains the most. The close temporal relationship between rainfall and bacterial contamination is particularly evident at Souq al Jomaa (r = 0.78). The only exception to this was in Tripoli, where there was a very high level of bacterial contamination (95%) in July of 1993, with no rain falling, indicating a localized, episodic event occurred during that period.

Waterborne disease cases
Table 5 presents annual cases by sex. A total of 1,748 cases were recorded, with 62% female. The highest

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number occurred in 1994 (431 cases), coinciding with high contamination prevalence (Tripoli 77.8%, Souq al Jomaa 62.4%). The lowest was in 1992 (164 cases).

Table 5. Annual waterborne disease cases by sex (1990–1995)

Year	Male	Female	Total
1990	183	193	376
1991	69	116	185
1992	29	135	164
1993	81	188	269
1994	179	252	431
1995	123	200	323
Total	664 (38%)	1,084 (62%)	1,748

Relationship between contamination and disease

The correlation between average annual contamination prevalence (average of Tripoli and Souq al Jomaa) and annual disease cases was moderate but not statistically significant ($r = 0.68$, $p = 0.14$, $n=6$). While not providing strong statistical evidence, the qualitative pattern shows that years with higher contamination (e.g., 1994) also had higher disease counts. Most disease cases occurred in winter, coinciding with contamination peaks.

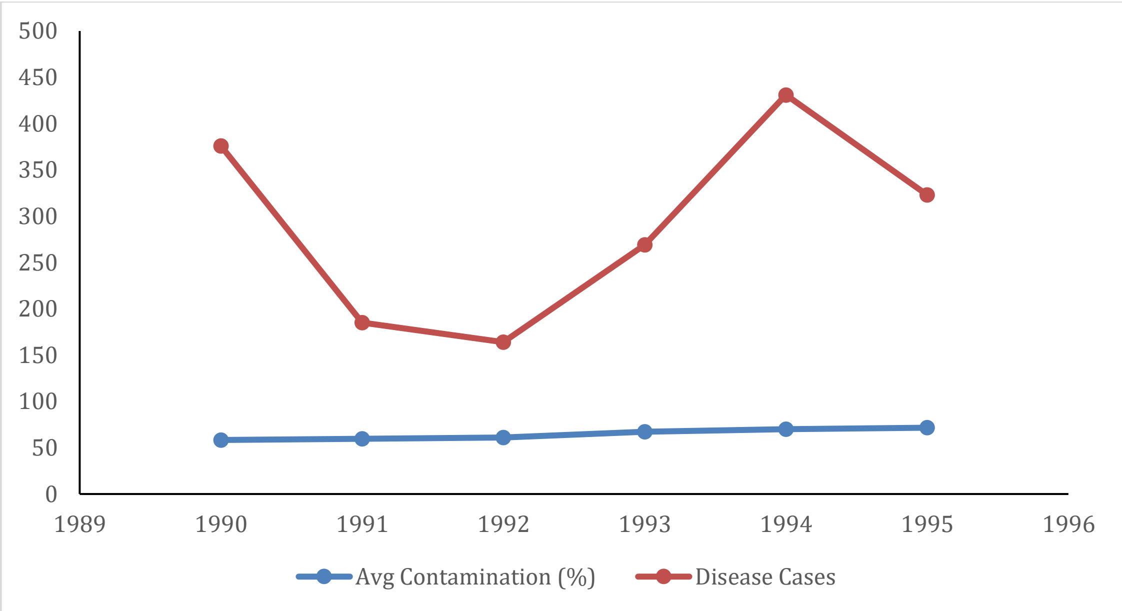

Figure 4. Relationship between average annual contamination prevalence and waterborne disease cases (1990–1995)

There is a moderate positive linear regression trend shown in the scatterplot graph (contamination increasing leads to increased illness or the number of cases of disease). Correlation from Pearson's $r = 0.68$ ($p = 0.14$, $n=6$, NOT SIGNIFICANT) is a result of only having 4 years with data for illness; however, it does appear to support findings that show this relationship exists. The irregularity in 1990 is likely due to extreme wet weather at that time, and its effects on the health of the population were delayed, leading to increased reported health problems later on in the year(s) following the weather event.

Well depth and seasonal sensitivity (aggregate comparison)

Wells in Souq al Jomaa (mean depth 14 m) showed larger seasonal amplitude (27 percentage points) and stronger rainfall correlation ($r = 0.78$) than Tripoli (22 m, 13 points, $r = 0.52$). This aggregate comparison supports the hypothesis that shallower wells are more vulnerable, but does not constitute a per-well depth response analysis.

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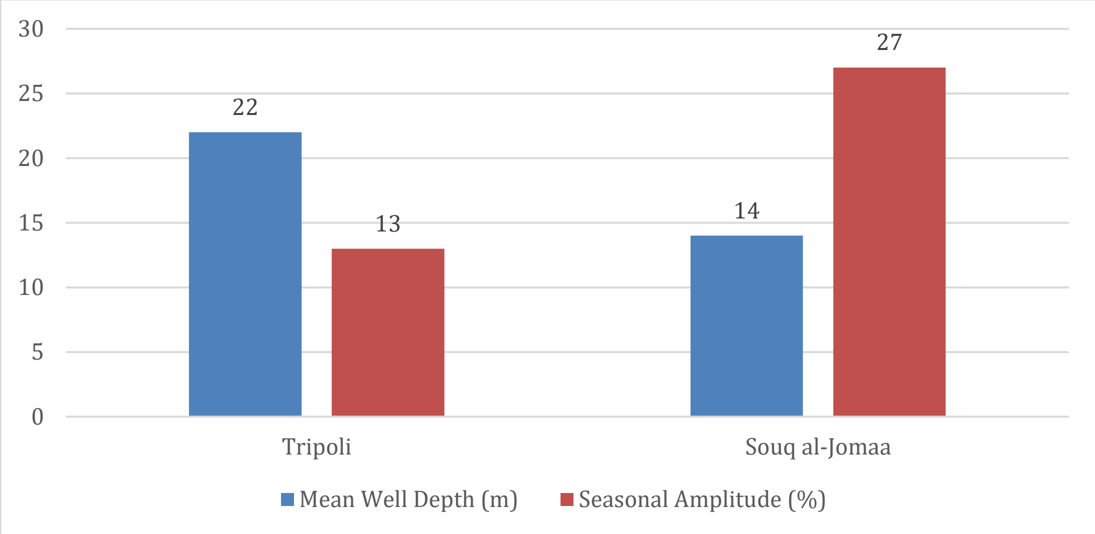

Figure 5. Relationship between mean well depth and seasonal contamination amplitude (winter minus summer)

The scatter plot shows an inverse relationship: shallower wells exhibit larger seasonal amplitude. This supports the hypothesis that shallower aquifers are more responsive to seasonal rainfall and surface contamination. However, because only two depth values (area averages) are available, a formal regression is not possible.

Temporal trends

The Mann-Kendall test applied to annual prevalence rates (1990–1995) revealed no statistically significant trend for Tripoli ($\tau = 0.60$, $p = 0.14$) or for Souq al Jomaa ($\tau = 0.73$, $p = 0.08$). Disease cases also showed no significant trend ($\tau = 0.33$, $p = 0.46$). The six-year series is short, and the test has low power to detect gradual trends with n=6; therefore, the "no significant trend" finding should be interpreted with caution.

Summary of statistical tests

Table 6. provides a concise summary of the main statistical findings

Variable / Comparison	Statistical Test	Test Statistic	p-value	Interpretation
Prevalence: Tripoli vs. Souq (6-year mean)	Mann-Whitney U	U = 0	< 0.01	Significant (higher in Tripoli: 70.4% vs. 56.5%
Seasonal variation (Tripoli)	Repeated-measures ANOVA	$F_{(3,140)}$ = 5.68	= 0.001	Significant seasonal effect
Seasonal variation (Souq)	Repeated-measures ANOVA	$F_{(3,140)}$ = 12.34	< 0.001	Significant seasonal effect
Rainfall vs. contamination (Tripoli)	Pearson correlation	r = 0.52	< 0.05	Moderate, positive correlation
Rainfall vs. contamination (Souq)	Pearson correlation	r = 0.78	< 0.01	Strong, positive correlation
Annual contamination vs. disease cases	Pearson correlation	r = 0.68	= 0.14 (NS)	Not significant (n=6)
Temporal trend (Tripoli prevalence)	Mann-Kendall	τ = 0.60	= 0.14 (NS)	No significant trend
Temporal trend (Souq prevalence)	Mann-Kendall	τ = 0.73	= 0.08 (NS)	No significant trend

NS = not statistically significant

Discussion

Spatial disparities: urban pressure as the main driver

The significantly higher E. coli contamination prevalence in Tripoli (70.4% vs. 56.5%) and higher winter intensity (79% vs. 71%) align with H_1. This is consistent with global findings that dense urban areas with aging sanitation infrastructure suffer higher fecal contamination of shallow groundwater [29-32]. There is a moderate positive linear regression trend shown in the scatterplot graph (contamination increasing leads to increased illness or the number of cases of disease). Correlation from Pearson's r = 0.68 (p = 0.14, n=6, NOT SIGNIFICANT) is a result of only having 4 years with data for illness; however, it does appear to support findings that show this relationship exists. The irregularity in 1990 is likely due to extreme wet weather at

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that time, and its effects on the health of the population were delayed, leading to increased reported health problems later on in the year(s) following the weather event.

Rainfall is the primary driver of seasonal contamination
The strong positive correlations (r = 0.78 for Souq al Jomaa, r = 0.52 for Tripoli) provide direct evidence that rainfall triggers winter contamination peaks, confirming H_2. The mechanism: rainfall mobilizes fecal material via surface runoff and rapid recharge [33-35]. The summer decline is due to the absence of rain, high temperatures, and UV radiation [36]. The exceptionally wet year 1990 (420 mm) produced very high contamination indices, while drier years still showed winter peaks but with slightly lower intensity.

Health burden and temporal concordance
The total of 1,748 waterborne disease cases over six years represents a substantial burden. There was a very strong seasonal correlation in annual disease incidence with peak occurrence of contamination, with a moderate correlation (r=0.68) between overall annual contamination and disease, although not statistically significant, which could be biologically expected. Female cases accounted for approximately 62% of reported cases, likely due to socialized roles of women (gender) in water handling and household responsibilities [38, 39]. The greatest number of reported cases occurred in 1994 (431), along with the highest reported contamination occurrence.

Groundwater Management and Climate Resilience Implications
The relationship between rainfall variability and groundwater contamination has significant implications for managing water resources in urban arid and semi-arid areas. Climate predictions for the Mediterranean and North Africa indicate there will be greater variability in rainfall in the future, with more frequent extreme rain events mixed in with longer dry periods [40]. These extreme events may increase the risk of episodic microbial contamination of shallow aquifers through increased surface runoff and rapid infiltration rates. Therefore, groundwater protection strategies need to use climate-resilient methods such as upgraded sanitation systems, wellhead protection, and routine microbiological monitoring during high-risk periods.

Strengths and limitations
Strengths: Large sample (2,428 wells), six-year duration, reference method for E. coli, integration of rainfall and health data, sex disaggregated disease records. Despite its strengths, this study has several limitations. To start with, the historical nature of the dataset limits how much information is available for each well with respect to hydrogeologic characteristics (e.g., well construction), groundwater flow characteristics, and how each well depth affects groundwater levels and quality. Additionally, the disease data available are only in an aggregated form, which means that direct exposure-response relationships between contaminated wells and disease cannot be established. Finally, an observational design allows us to establish temporal associations, but it is not possible to draw causal conclusions. Nonetheless, the consistency of observed patterns across the study years provides strong evidence of the effect of environmental factors on groundwater contamination.

Limitations:
•Statistical unit ambiguity: Annual prevalence uses only six data points per area; monthly analysis uses aggregates.
•Convenience sampling: Results may not represent all wells in the region.
•Self reported depths: Unverified; only area averages available.
•Single hospital health data: Likely underestimates disease burden; no standardized diagnostic criteria.
•Short time series: Low power for trend detection.
•Observational design: Cannot establish causality.
•No individual-level linkage between well contamination and disease cases.
Despite these limitations, the consistency of seasonal patterns across six years provides useful information for local water safety planning.

Recommendations
1. Regulatory action: Enforce well drilling permits, sanitary seals, and setbacks from sewage.
2. Pre-winter disinfection: Distribute household chlorination tablets (e.g., NaDCC) before the rainy season (October–November).
3. Well protection: Enforce sanitary seals and elevated platforms, especially for shallow wells.
4. Routine monitoring: Quarterly E. coli testing, with increased frequency after rainfall.
5. Public awareness: Inform well owners about boiling water in winter.
6. Future research: Longitudinal studies with per-well depth measurements and multi-hospital health data are needed to confirm associations.

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Conclusion

Spatial inequality: Tripoli had higher E. coli prevalence (70.4% vs. 56.5%) and winter contamination levels (79% vs. 71%). Rainfall association: Monthly rainfall correlated positively with contamination (r = 0.78 and 0.52), suggesting winter rains contribute to contamination peaks. Shallow well vulnerability: The area with shallower wells (Souq al Jomaa, mean 14 m) showed larger seasonal variation. Health burden: 1,748 waterborne disease cases (1990–1995) with winter peaks coinciding with contamination; however, the annual correlation was not statistically significant. Stability: No significant temporal trend was detected over the six years, but the short series limits interpretation. Practical implication: Seasonal well protection and pre-winter disinfection are recommended to reduce contamination and potential health risks. Overall, the findings indicate that groundwater microbial contamination in the Tripoli region is driven by the interaction of urban environmental pressures and seasonal climatic variability. While Tripoli exhibited persistently elevated contamination levels, Souq al-Jomaa demonstrated stronger seasonal responsiveness to rainfall. These contrasting patterns highlight the importance of considering both anthropogenic and hydroclimatic factors when developing groundwater protection strategies in rapidly growing urban environments.

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