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Analysis of sunscreens and antibiotics in groundwater during the Covid-19 pandemic in the Riviera Maya, Mexico

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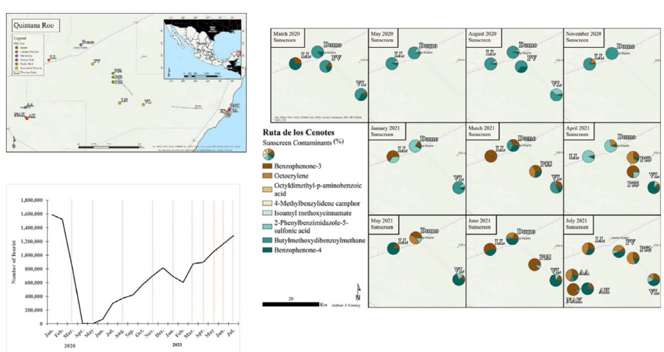
HIGHLIGHTS

- Pandemic was a natural experiment to determine groundwater pollution due to tourism.
- Tourists contribute to the diversity of sunscreen found in groundwater.
- Residents are major contributors of total concentration of contaminants.
- New sewage system effectively reduces contamination in groundwater.

GRAPHICAL ABSTRACT



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ABSTRACT

Tourism contributes to groundwater pollution, but quantifying its exact impact is challenging due to the presence of multiple pollution sources. However, the COVID-19 pandemic presented a unique opportunity to conduct a natural experiment and assess the influence of tourism on groundwater pollution. One such tourist destination is the Riviera Maya in Quintana Roo, Mexico (specifically Cancun). Here, water contamination occurs due to the addition of sunscreen and antibiotics during aquatic activities like swimming, as well as from sewage. In this study, water samples were collected during the pandemic and when tourists returned to the region. Samples were taken from sinkholes (cenotes), beaches, and wells then tested using liquid chromatography for antibiotics and active ingredients found in sunscreens. The data revealed that contamination levels from specific sunscreens and antibiotics persisted even when tourists were absent, indicating that local residents significantly contribute to groundwater pollution. However, upon the return of tourists, the diversity of sunscreen and antibiotics found increased, suggesting that tourists bring along various compounds from their home regions. During the initial stages of the pandemic, antibiotic concentrations were highest, primarily due to local residents incorrectly using antibiotics to combat COVID-19. Additionally, the research found that tourist sites had the greatest contribution to groundwater pollution, with sunscreen concentration increasing. Furthermore, installation of a wastewater treatment plant decreased overall groundwater pollution. These findings enhance our understanding of the pollution contributed by tourists in relation to other pollution sources.

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1. Introduction

Tourism is one of the world's most important industries for economic growth and employment, with a billion and a half people travel to foreign locales in 2019 (United Nations World Tourism Organization, 2020). Half of all travelers choose coastal destinations for their vacations, making coastal tourism a rapidly growing industry in the world (Sánchez-Quiles and Tovar-Sánchez, 2015; United Nations, 2017). Tourism can bring economic prosperity to a community, but it can also bring unintended consequences. Common issues affecting coastal communities include deterioration of the natural landscape, influx of waste products from human activity, declining air and water quality, and the primary and secondary effects of urbanization (Sánchez-Quiles and Tovar-Sánchez, 2015; Sunlu, 2003). An example of a coastal community where tourism is the only industry is the Riviera Maya and Cancún in Quintana Roo, Mexico (Casas-Beltrán et al., 2021; Hernández-Pedraza et al., 2020). The tourism industry is integral to the economic success of the area since there are no other sources of economic activities in the area such as farming and manufacturing. Any dip in tourism can generate massive unemployment and a subsequent decline in residents' safety, security, and well-being (Chávez et al., 2020).

When the World Health Organization declared COVID-19 a pandemic on March 11, 2020, the United Nations World Tourism Organization (2021) announced that world tourism plummeted by 74 %. The Mexican government officially declared the disease a health emergency at the end of March 2020, canceling non-essential activities for people considered high-risk for the disease and limiting in-person attendance at gatherings (Reuters Staff, 2020). Although Mexico never officially locked down its borders, local governments put mobility restrictions in place to prevent the unnecessary congregation of people, including closures of roads, beaches, and entertainment venues (Riviera Maya News, 2020a, 2020b, 2020c). The number of passengers arriving in Cancún by air from January 2020 to April 2020 fell by 36.0 % from the previous year (Undersecretariat of Planning and Tourism Policy, 2020).

The reduction of tourist activities in Quintana Roo allowed a natural experiment to investigate how tourism affects water resources. Water resources tend to be exploited by tourists and the tourism industry, leaving communities with issues of water quality and availability (Sánchez-Quiles and Tovar-Sánchez, 2015; Sunlu, 2003). Downs et al. (2022) found an increase in water pollution when tourist activities increased in natural areas susceptible to degradation. Understanding the scale of tourism's impact on groundwater can be difficult due to the lack of information on tourist behavior and the inconsistency of tourist visits (Casas-Beltrán et al., 2021). The COVID-19 pandemic allowed for a better understanding of the impact of human during tourism from aquatic activities such as swimming and sewage disposal on groundwater resources in a coastal community.

Differentiating various categories of human activities within a shared watershed presents a challenging task. To assess their impact, researchers have employed surrogate measures of human activities using sunscreens and antibiotics that serve as tracers for human activities. Sunscreens are commonly used to safeguard against harmful UVA and UVB rays, but their residues permeate water bodies when individuals engage in activities such as swimming, bathing, showering, using restroom facilities, or laundering clothes (Díaz-Cruz & Barceló, 2009; Li et al., 2007; Molins-Delgado et al., 2015; Poiger et al., 2004). Similar to sunscreens, antibiotics are directly introduced into water systems through human activities. Antibiotics can enter water systems via medication usage or dietary exposure, subsequently being excreted as waste into these systems (Hu et al., 2022; Wang et al., 2022; Zeng et al., 2020).

Other researchers have examined pharmaceuticals and personal care products (PPCPs) during the COVID-19 period (Chen et al., 2021; Stipanicev et al., 2022; Lin et al., 2023), but none have explored the ramifications of reduced tourism on water resources. Their findings indicate that the temporary disruption caused by the COVID-19 pandemic weakened the influx of PPCPs into Bohai Bay, China resulting in diminished cumulative pollutant effects (Lin et al., 2023). The consumption PPCPs for controlling and preventing COVID-19 likely surged during the pandemic, but it did not result in significant pollution in lakes and wastewater treatment plants (Chen et al., 2021). Another study confirmed that COVID-19 lockdown led to lower cumulative concentrations and mass flow of measured pharmaceuticals such as antibiotics and steroidal anti-inflammatory drugs in the Sava and Drava Rivers, Crotia (Stipanicev et al., 2021).

The aim of this study was to assess the influence of tourist activities on groundwater resources in a coastal community by examining the absence of tourism during the COVID-19 pandemic and the subsequent resumption of tourist influx. The hypothesis is that with a decrease in tourism and tourist activities, there would be a decrease in the concentrations of sunscreen and antibiotics in locations commonly visited by tourists. The second hypothesis of this study was that changing from septic systems to wastewater treatment plants along the beach would decrease the amount of contaminants in groundwater even as tourists returned to the area. This study used the Riviera Maya/Cancun area as a model for other coastal communities with tourism because tourism and the local communities that live there only influence this region's groundwater.

2. Study area

2.1. Geologic and hydrogeologic setting

The Yucatán Peninsula is in southeastern Mexico, jutting out in a north/northeasterly direction, bounded by the Gulf of Mexico and the Caribbean Sea, and consists of three states: Campeche, Yucatán, and Quintana Roo. The study area focused on the northern part of Quintana Roo that includes Cancún and the Riviera Maya (Fig. 1). Circles on the map indicate sampling sites. Abbreviations next to the sites are map codes used to differentiate sites from one another. Sampling sites included sinkholes (locally known as cenotes), wells, and beach locations across the state from west to east (Table 1). Included in the table are distances from sites to the eastern coast using straight-line horizontal distances measured in ArcGIS Pro. Each site has a corresponding brief description of use (Table 1 and Fig. 1). The levels of tourist use include *limited* or *tourism*. The definition of *limited tourism* used in this study is that the use of the location was not predominantly for tourism, whereas *tourism* is defined as total or complete use of the location. The *not in use* description is defined as a location not used for tourism.

The Great Mayan Aquifer underlies most of the Yucatán peninsula, creating the world's largest continuously connected cave system, approximately 2000 km^2 (Escolero Fuentes, 2007; Moreno-Pérez et al., 2021). The aquifer provides the only source of freshwater for the inhabitants of the region and the ecosystem is considered groundwater dependent (Bauer-Gottwein et al., 2011; Saint-Loup et al., 2018; Villasuso and Méndez-Ramos, 2000). The aquifer rapidly recharges due to the flat landscape and the thin soil profile and discharges to the oceanic basins via lagoon conduits and underwater springs (Bauer-Gottwein et al., 2011; Escolero Fuentes, 2007; Saint-Loup et al., 2018; Villasuso and Méndez-Ramos, 2000). Geological map of the region and land use map are provided in Supplemental materials (Figs. S1 and S2).

Studies describing the flow of groundwater through the aquifer in this region are few. The current understanding of groundwater flow in the state is incomplete and/or contradictory (Bauer-Gottwein et al., 2011). Saint-Loup et al. (2018) describes Quintana Roo's aquifer as coastal, although groundwater flows northward toward the Gulf of Mexico in the Holbox Fracture Zone. McKay et al. (2020) state the flow paths and rates through the Holbox Fracture Zone, a series of linear fractures running directionally north to south, are not well understood due to the complexities of the features.

Groundwater in Quintana Roo is used for domestic, commercial, and recreational purposes (Escolero Fuentes, 2007; Hernández-Terrones et al., 2011; Leal-Bautista et al., 2013; Marín, 2007). Geology, population growth (temporary and permanent), increased recreation, and poor wastewater disposal and treatment practices make the aquifer highly susceptible to contamination through direct or indirect sources (Escolero Fuentes, 2007; Hernández-Terrones et al., 2011; Leal-Bautista et al., 2013; Marín, 2007;

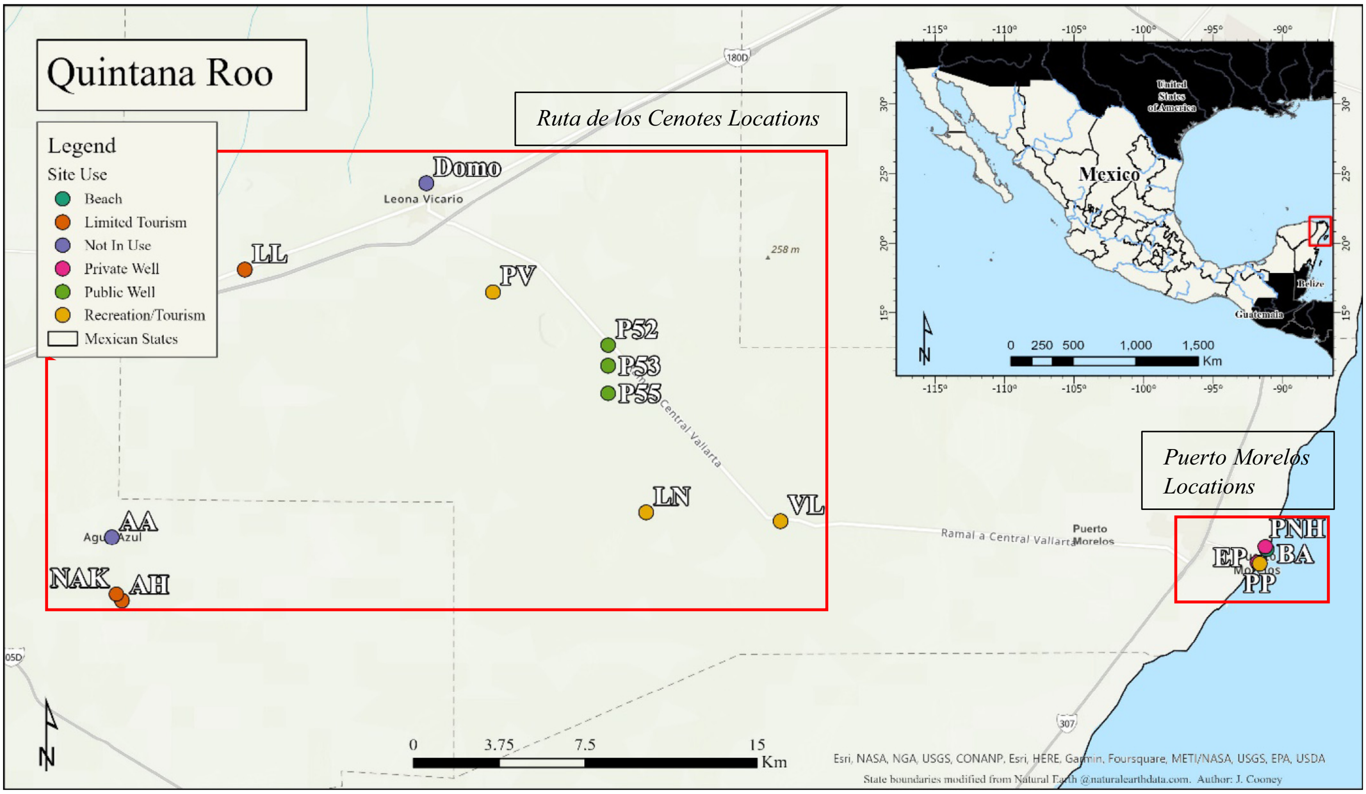

Fig. 1. Map of reference area in northern Quintana Roo, Mexico. Sampling sites are indicated in circles with the type of location indicated in different colors with description found in Table 1. The sites are divided into two sections - Ruta de los Cenotes and Puerto Morelos. The beach location PNH is in the beach sites. The geological setting for the locations is composed of undifferentiated, diagenetically immature carbonates from the Miocene to Holocene age (Fig. S1) (Bonet and Butterlin 1962; Lopez-Ramos 1975). The land use of the majority of the area is sub-tropical broadleaf evergreen forest (Fig. S2).

Metcalfe et al., 2011; Moore et al., 2019). Pinpointing a source of direct contamination is difficult because a contaminant can enter the system through a leaky septic tank or a tourist swimming in a cenote. A contaminant can quickly spread through the interconnected aquifer (Bauer-Gottwein et al., 2011; Hernández-Terrones et al., 2011). Regulations concerning the use or protection of water in these landforms are lacking (Casas-Beltrán et al., 2020a).

2.2. Tourism

Quintana Roo's economy is heavily dependent on tourism, comprising 87 % of the state's gross domestic product (Espejel and Sherman, 2021). The Mexican government deliberately constructed Cancún to create an international tourist destination to attract American tourists to revitalize local and national economies (Dunphy, 1972; Kandelaars, 2000). Tourist visits have increased consistently since the establishment of the city and the Riviera Maya. Tourists can now be considered a permanent, large, and continuous presence (Brown, 2013). From 1992 to 2019, the total number of tourists progressively increased every year. Percentages of occupied hotel rooms hovered consistently around 70 % to 75 % from 2019 to the first quarter of 2020.

The COVID-19 pandemic caused the steep drop in tourism, with Quintana Roo's tourism visits dipping as low at 1530 in May 2020 and Cancún's hotel rooms only 30.4 % occupied in September 2020, although it is not clear whether the percentage of rooms occupied was calculated from the total amount of rooms in hotels or from the limited number of rooms available due to hotel-room occupancy restrictions (*Yucatan Times*, 2022). Countries instituted and enforced border closures and quarantine requirements for all travelers, dissuading would-be tourists from international travel (Onyeaka et al., 2021). Transportation providers could not fill passenger seats due to low consumer demand and capacity limits. Hotels, restaurants, and sports and entertainment venues closed. Governments enforced strict attendee limits on outdoor activities (Onyeaka et al., 2021). Some restrictions in Mexico paralleled those in the rest of the world when the governmental departments (Secretaría de Salud and the Subsecretaría de Prevención y Promoción de la Salud) announced and encouraged work-from-home procedures, school closures, and mobility restrictions (Riviera Maya News, 2020a). State and municipal governments in Quintana Roo took a hard-line stance to COVID-19 restrictions. Puerto Morelos's municipal government closed and policed beaches (Riviera Maya News, 2020c). Cancún closed beaches as well as instituted random temperature and health assessments throughout the city. Solidaridad closed streets and beaches and installed check points on major routes into and out of the municipality. Tulum enforced curfews and limited alcohol sales to certain times of the day (Riviera Maya News, 2020c).

Table 1
Sampling locations descriptions, use, and distance to coast.

Site abbreviation	Site description	Use	Straight line distance to eastern coast (km)
AA	Cenote	Not in use	47.36
AH	Cenote	Limited tourism	45.07
BA	Well	Beach	0.10
Domo	Cenote	Not in use	39.40
EP	Well	Private well	0.12
LL	Cenote	Limited tourism	45.88
LN	Cenote	Tourism	25.75
NAK	Cenote	Limited tourism	45.62
P52	Well	Public well	30.50
P53	Well	Public well	30.17
P55	Well	Public well	29.69
PNH	Well	Private well	0.019
PP	Beach	Tourism	0.03
PV	Cenote	Tourism	35.45
VL	Cenote	Tourism	20.32

Tourist numbers rebounded faster than the percentage of occupied hotel rooms. Visitors to Quintana Roo returned beginning in June 2020 and continued in July 2020, although at a gradual pace. Limited numbers of tourists stayed at hotels because the COVID-19 hotel occupancy restrictions (*Yucatan Times*, 2022). Tourists chose to stay at vacation rentals such as Airbnb since public health guidelines did not limit their occupancies (*Yucatan Times*, 2021, 2022). Vacation rental occupancies reached as high as 50 % and logged stays of 28 days or more, longer than a normal tourist stay, as the industry bloomed during the crisis (*Yucatan Times*, 2021, 2022).

3. Materials and methods

3.1. Sampling and analytical methods

The sunscreens and antibiotics tested for in this study are compounds common in tourist locations (Tables S1 and S2). For sunscreens, this study focused on organic UV-filter sunscreens. Casas-Beltrán et al. (2020b) found the most common sunblock brands among tourists were Coppertone, Banana Boat, Nivea, and Hawaiian Tropic. Common active ingredients used by these brands include octocrylene, 4-methylbenzylidene camphor, and butylmethoxydibenzoylmethane (avobenzone), while the Banana Boat brand was the only one that used benzophenone-3 (oxybenzone). Antibiotics are commonly prescribed for various ailments. Tylosin, a veterinary drug, was also included in the study.

Water samples from March 2020 to July 2021 at the start of the pandemic and through increasing number of tourist returning to the sites (Fig. 2). Sites included cenotes, showers at recreational water areas, public and private wells, and beaches (Table 1). Site selection was based on the site's accessibility during the pandemic. Pandemic closures prevented sampling of all sites during sampling times.

Water samples were collected by grab sample at the surface or after 10 min flushing for wells into either amber glass bottles or new plastic containers (all 1 L) that were rinsed three times with distilled water. Powdered ascorbic acid at 10 mg was added to each sample to preserve the sample without dilution of the contaminants. Each sample was placed into a −20 °C freezer. Samples were then transported to Southern Illinois University – Edwardsville where all samples were prepared and chemically analyzed using liquid chromatography in accordance with modified methods (Avila et al., 2021; Rodil et al., 2008; Rodriguez et al., 2021; Tucker et al., 2019).

3.2. Statistical analysis and data plotting

Results were tabulated and graphed in Microsoft Excel version 2206. Multiple samples taken at the same site on the same date were averaged to get the average contamination. Results were mapped using ESRI's ArcGIS Pro version 2.9.3 to visually inspect the relationship between contamination levels over time as tourists returned. A two-tailed Wilcoxon matched-pairs signed-ranks test was used to quantitatively analyze the relationship at the 95 % confidence interval with $\alpha = 0.05$ (McGrew et al., 2014). Assumptions for the test required sample pairs to be chosen at random (McGrew et al., 2014); however, the samples were not chosen at random due to great variability in the geologic and hydrogeologic characteristics within a karst aquifer (Ford and Williams, 2007; Villasuso and Méndez-Ramos, 2000). Because each site within the study area may have different flow characteristics than other sites, pairs were specifically chosen to eliminate the possibility of rendering the results useless. Additionally, sites were chosen if they were collected during the same months in both 2020 and 2021. The purpose of the time constraint was to reduce the effect of precipitation on concentrations. A month that is characteristically drier would have less dilution than a month with higher precipitation on average.

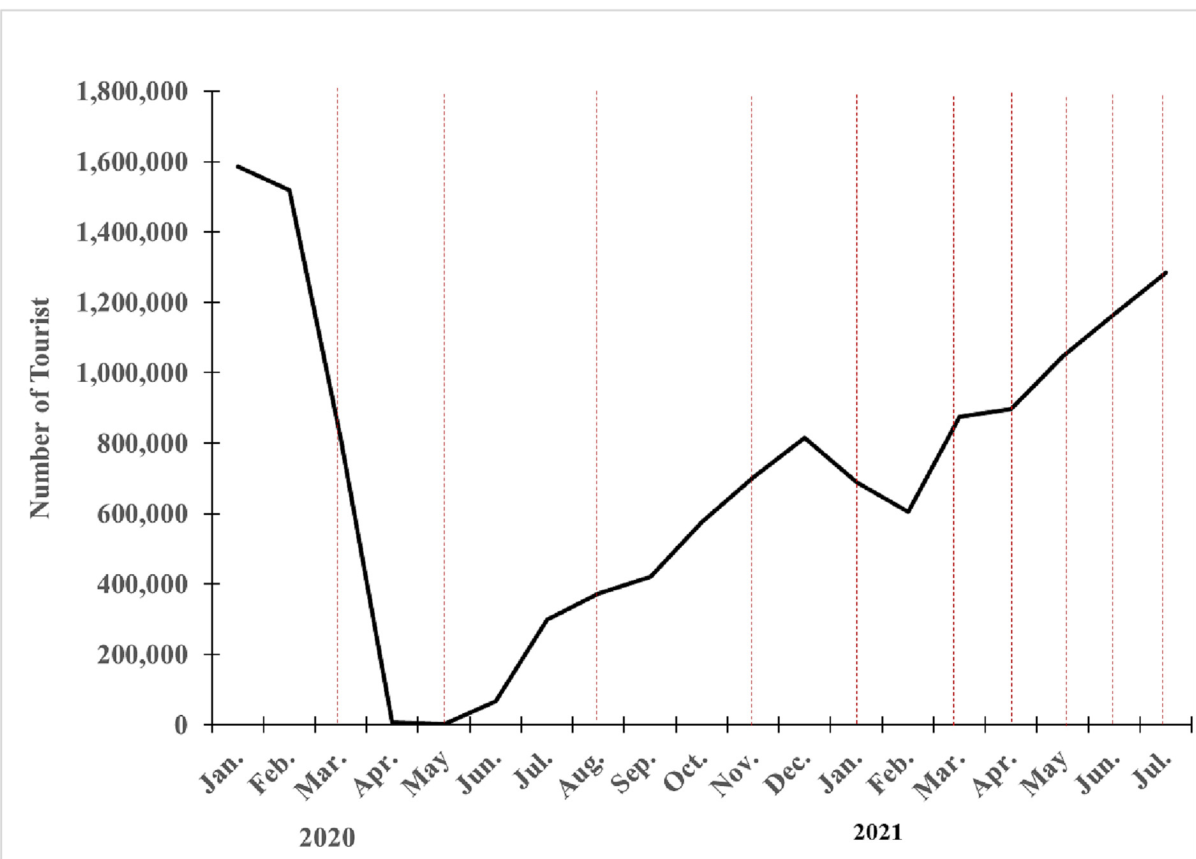

Fig. 2. Number of tourist visit Cancun during sampling period. The red dashed lines indicate months that sampling occurred (Secretaría de Turismo, 2021).

Therefore, the possibility of a reduction of concentrations due to dilution by higher precipitation would introduce another variable that could reduce the effectiveness of the statistical test. Sample pairs were placed in columns that corresponded to the year of collection.

The PNH locations were separated from the main dataset to answer the second question of this study. The sample size of PNH locations is small, too small to meet the assumptions required for statistical analysis. Therefore, the PNH location are qualitatively discussed. Statistical analysis and boxplots were generated in IBM SPSS version 28.0.1.

4. Results

4.1. Sunscreens

4.1.1. Concentration of sunscreens

People wear sunscreens to protect against harmful UVA and UVB rays. Sunscreens leach into the water when a person swims, bathes, takes a shower, uses restroom facilities, or washes clothes (Díaz-Cruz & Barceló, 2009; Li et al., 2007; Molins-Delgado et al., 2015; Poiger et al., 2004). The concentration of sunscreen in different types of water use can provide insight into potential sources and quantification of tourism's effect on groundwater (Fig. 3A). Total sunscreen concentration for each sampling time (Fig. 3B), including sites along the Ruta de los Cenotes, Puerto Morelos, and the beach location (PNH), ranged from below detection limit to 32,900 ppb, with a mean of 1457.89 ppb and a standard deviation of 5637.59. The total concentration of all sunscreens for each location type indicates that tourism is the largest contributor of sunscreen (Fig. 3A). In terms of concentrations by water use, the concentrations were highest in recreational locations, followed by wells, sites not used, limited tourism locations, and beaches, in that order.

The overall total concentration per sampling time remains similar (Fig. 3B) even when COVID decreased the number of tourist (Fig. 2) thus showing that both locals and tourism contribute to pollution throughout the year. In 2020 and 2021, the inland locations along the Ruta de los Cenotes (Fig. 4A) show wide variability from site to site and month to month. In 2020, total concentrations peaked in May and August and were the lowest in March and November. In 2021, total concentrations started off very low in January and gradually increased through March and peaked in April. The concentrations decreased in May, although not to the low levels of January, and gradually increased again to another peak in July. Generally, the sites in 2020 had higher concentrations than in 2021, although the April 2021 was equal to or larger than the 2020 months. Greater variability occurred in 2021 than in 2020.

The difference in total concentrations between 2020 and 2021 is more obvious when looking at the beach locations of Puerto Morelos (see Fig. 4B). During 2020, the total concentrations were higher in March, August, and November, with November being the highest. PP in November 2020 had a significantly high total concentration, greater than any other site. EP in August 2020 came closest to the highest total concentration. The second part of the study period saw significantly smaller total concentrations than 2020, with the largest concentrations occurring in April 2021, corresponding to similar concentrations in the inland areas during the same month. For the beach locations, most of 2021 saw a narrower range of variability than 2020.

4.1.2. Composition of sunscreen

Tourism changed the composition or type of sunscreen present. When the pandemic started, the types of sunscreen reflect the types used by locals while when the tourism number increased (Fig. 3B) so did the types of compounds found the different locations (Fig. 4A) Component sunscreens recorded at each site were mapped using pie charts (Fig. 4A and B). Maps of 2020 and 2021 show an obvious difference in detected active ingredients in samples. Trends from the Ruta de los Cenotes continued to the beach locations in the Puerto Morelos map (Fig. 4B).

Maps show the spatial distribution of the contaminants in relation to their environment (Fig. 4A and B). Total concentrations were lower along the Ruta de los Cenotes in the interior of the state than in the beach locations of Puerto Morelos in 2020. Compositionally, inland sites matched beach locations. The percentages of the active ingredients in the samples may not have matched exactly; those components that were a large proportion in an interior location were also proportionally significant in the beach locations. The trend continued throughout the study period.

4.1.3. Statistical analysis of sunscreen data

For this research project, there was a total of 59 samples in this dataset, with some samples averaged together if multiple samples were taken at the same site, excluding the PNH samples. The test sample had eight matched pairs in two groups by year for a total of 16 individual samples. For the Wilcoxon matched-pairs signed-ranks test, five locations (BA, PP, LL, Domo, and VL) were chosen based on the criteria discussed previously and are from both inland and beach locations with varying types of use (Table 2). The chosen months were either March or May in both years. The null hypothesis was that there was no difference between the 2020 (low tourism) and 2021 (high tourism) concentrations, whereas the alternative hypothesis was that there was a difference. The two-tailed test generated a $z = 0.560$ (critical value $= \pm 1.96$) with $p = 0.575$, resulting in the retention of the null hypothesis.

PNH was separated from the rest of the dataset to evaluate the new wastewater treatment in Puerto Morelos. The PNH location was mapped using the graduated pie charts method (Fig. 6A). This method maps the graduated increase and decrease in circle size based on total concentration of the size while at the same time seeing the active ingredients that make up the total concentrations. Much like the Puerto Morelos and Ruta de los Cenotes locations, PNH saw a change in total concentration and contaminant composition in 2021. After the connection to the wastewater treatment plant in 2021, the concentration of sunscreen decreased in the groundwater near the beach (Fig. 6A).

4.2. Antibiotics

4.2.1. Concentration of antibiotics

The antibiotics in this study are used to treat a myriad of illnesses as well as a prophylactic for traveler's diarrhea (Centers for Disease Control [CDC], 2019). Human exposure to antibiotics can be from medication or dietary exposure, which is then excreted in waste and into water systems (Hu et al., 2022; Wang et al., 2022; Zeng et al., 2020). Like sunscreens, antibiotics are directly put into water systems by human activities such as during swimming or in sewage, making it another indicator for temporary population increase. Similar to sunscreens, the antibiotic contamination by use type was dominated by recreational/tourism (Fig. 3A). The recreational sites had the highest total concentration. The not in use classification was more contaminated than other uses, including limited tourism.

Total antibiotic concentration during each sampling time showed where highest at the start of the pandemic and then again when tourist number were highest (Fig. 3B). Antibiotic maps were created using the graduated pie chart technique, showing the interior locations had higher concentrations of antibiotics than the beach locations throughout the study period (Fig. 5). The largest concentrations and the largest variability among sites occurred in the interior sites along the Ruta de los Cenotes. While the beach locations had a higher total concentration in 2020, compared to each other, the beach sites had relatively stable total concentrations compared to the inland sites (Fig. 6B).

4.2.2. Composition of antibiotics

Composition of the antibiotics was more varied during 2020 (Figs. 3B and 5). Across all sites, most antibiotics were represented in the samples, although trimethoprim, sulfamethoxazole, and oxytetracycline were the most common. The samples from 2021 saw a reduction of variability in the composition of contaminants. Trimethoprim, sulfamethoxazole, and oxytetracycline were the most dominant antibiotics in both interior and beach locations during 2020 (Figs. 5 and 6B). Tylosin, a veterinary medicine, emerged in November 2020, with a concentration of 0.01 ppb. In

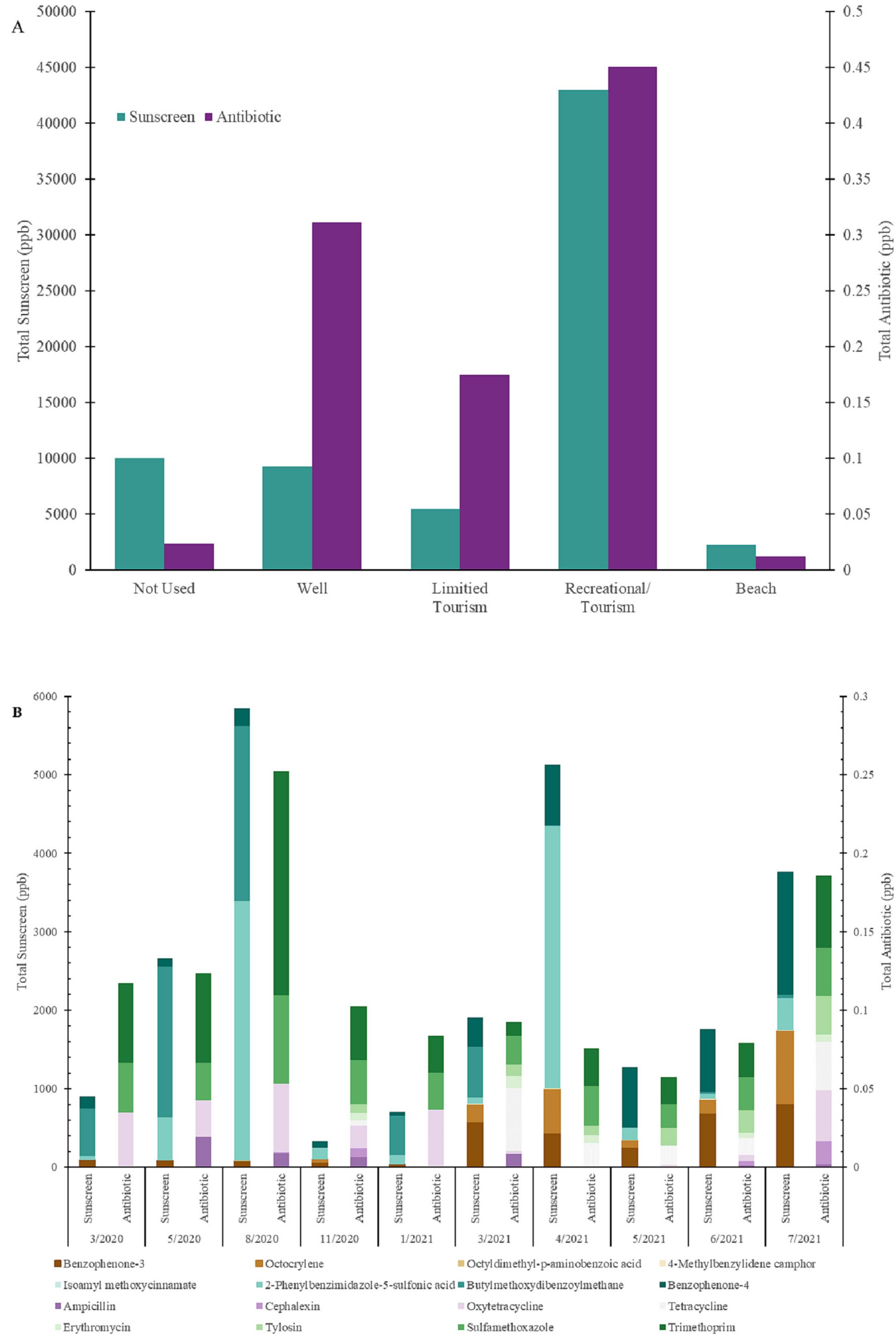

Fig. 3. A) Total amount of sunscreen and antibiotics per site type; B) Total sunscreen and total antibiotic per sampling date.

the following months, the concentration rose to its highest point in June 2021, when it reached 0.03 ppb, outranking other antibiotics such as tetracycline, oxytetracycline, erythromycin, cephalexin, ampicillin, and penicillin G. It outpaced cephalexin, penicillin, ampicillin, and erythromycin in August 2020. The beach location (PNH) indicated similar concentrations of antibiotics through all sampling times with the composition

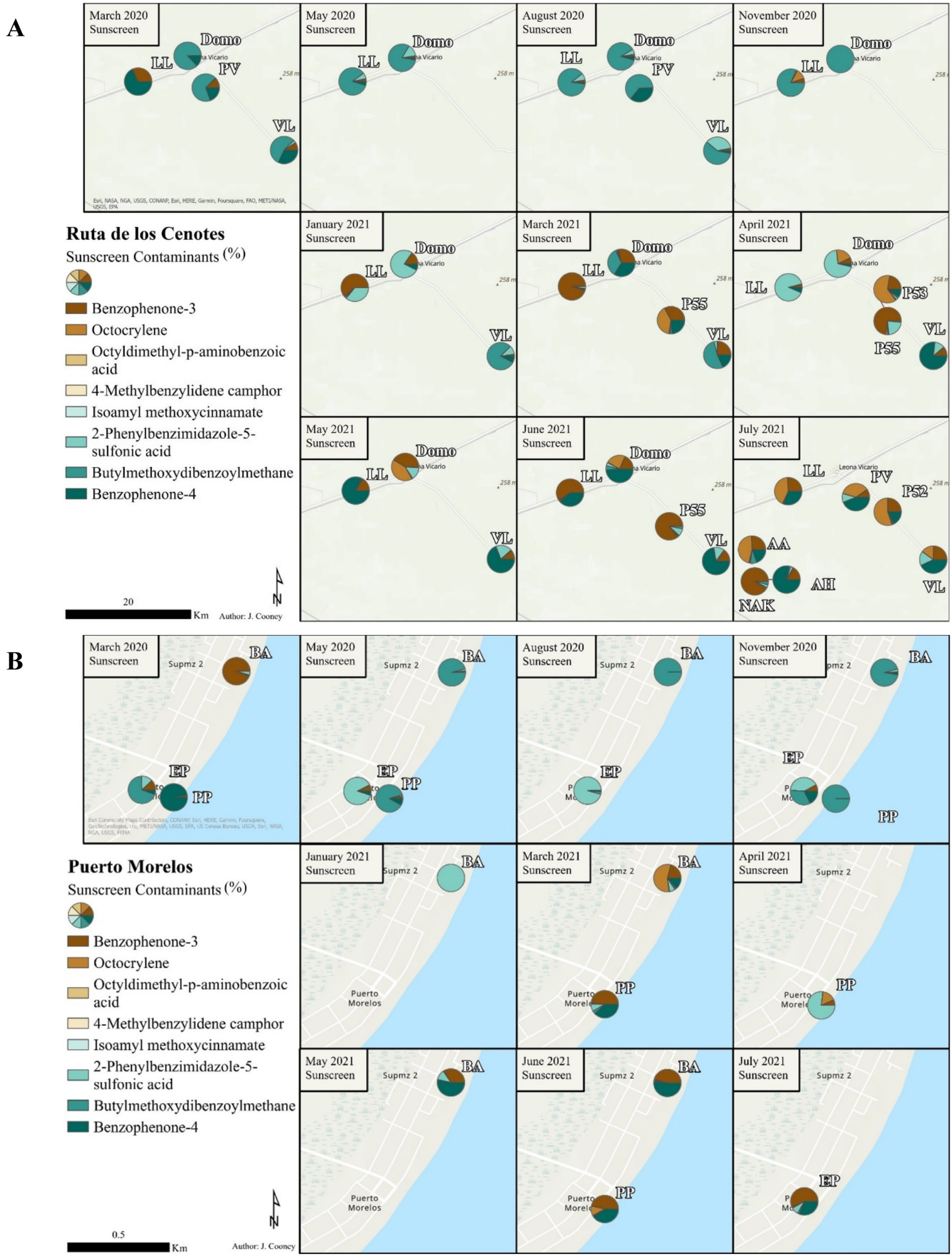

Fig. 4. Relative sunscreen proportions from March 2020 (upper left) to July 2021 (lower right). (A) Ruta de los Cenotes; (B) Puerto Morelos.

Table 2
Wilcoxon matched-pairs signed-ranks test sites and concentrations.

Site	Antibiotics (ppb)		Sunscreen (ppb)	
	2020	2021	2020	2021
03BA	0.003	0.015	9.546	273.835
05BA	0.182	0.009	188.543	120.760
03PP	0.024	0.019	11.791	111.147
03LL	0.009	0.002	13.894	92.735
05LL	0.015	0.008	527.808	425.463
03Domo	0.059	0.017	160.546	192.847
05Domo	0.067	0.009	1152.00	210.989
03VL	0.006	0.031	125.900	1071.270

changing even with the connection to the new wastewater treatment plan (Fig. 6B).

4.2.3. Statistical analysis of antibiotic data

For the Wilcoxon test, the same pairs and groups were used as the sunscreen Wilcoxon test, except the antibiotic total concentrations were used instead of the sunscreen total concentrations (Table 2). The hypotheses were similar as well. The null hypothesis stated there was no difference between the 2020 and 2021 samples. The alternative hypothesis stated there was a difference between the groups. The test was performed at the 95 % confidence interval with a p-value of 0.05. SPSS returned a test statistic of $z = -1.260$ (critical value $= \pm 1.96$) at a significance of 0.218, thus retaining the null hypothesis.

Beach locations saw less variability in the composition that to the interior samples in both 2020 and 2021. Trimethoprim, sulfamethoxazole, and tetracycline were the most prevalent. PNH in March 2021 and PP in June 2021 had the only two locations with an antibiotic that was other than the three prominent antibiotics (Fig. 5B). The mean for the five samples for PNH was 0.01 ppb and a standard deviation of 0.01. The minimum value was 0.00 ppb and the maximum value was 0.02 ppb for a range of 0.01 ppb.

PNH's total concentrations were lowest in January and April 2021. However, March 2020, March 2021, and May 2021 saw higher levels of concentrations at 0.01 ppb, 0.02 ppb, and 0.02 ppb, respectively. This pattern is different from the Ruta de los Cenotes and Puerto Morelos locations, where they saw higher antibiotic concentrations in 2020.

5. Discussion

The objective of this research was to evaluate the impact of tourist activities on groundwater resources in a coastal community by investigating the absence of tourism during the COVID-19 pandemic and the subsequent resurgence of tourist influx. The main hypothesis posits that a reduction in tourism and related activities would lead to a decrease in the levels of sunscreen and antibiotics in areas frequently visited by tourists. To serve as a representative model for other coastal communities with tourism, the study focused on the Riviera Maya/Cancun region, as tourism and local communities in this area uniquely impact groundwater resources.

Considering groundwater flows toward the coasts, any contaminant that enters the groundwater in the interior will discharge into seawater (Bauer-Gottwein et al., 2011). Because Quintana Roo is a major tourist destination, it is important to understand the extent of tourism's contribution to the problem. From March 2020 to November 2020, tourism had an interesting effect on sunscreens and antibiotics in groundwater. During the touristic low, two sunscreens and three antibiotics were still present. The study's hypothesis was that there would be an overall decline in sunscreen and antibiotic concentrations across the entire study area for the beginning of the pandemic and a steady increase in concentrations as tourism increased. However, continuous concentrations both sunscreens and antibiotics during 2020, when tourism was at its lowest, did not support the hypothesis.

It was difficult to know the natural variability due to permanent resident contribution to pollution but during the pandemic they were the only source in the groundwater. The high concentration of the outliers being limited to two sunscreen compounds and the considerable drop in concentrations in 2021 show that the local population utilized recreational areas in the absence of tourists and only use a couple different types of sunscreens. These peaks are magnitudes higher than other sunscreens and antibiotics in the dataset and cannot be attributed to tourists alone, considering the total number of tourists from March 2020 to November 2020 to the state was 3,261,101 (Secretaría de Turismo, n.d.) and the population of Quintana Roo was 1,857,985 in 2020 (Secretaría de Economía, n.d.), which is around a 60 % decrease in tourism. Two peak time periods occurred in August 2020 and November 2020. Tourists to Quintana Roo during those two months were 372,816 and 703,805 (Secretaría de Turismo, n.d.), far below the total population of the state. Locals preferred two sunscreens over all others, and the large quantities of these compounds showed they consistently applied sunscreen during their visits to the recreational water ways.

Site uses in conjunction with total concentration maps show residents were responsible for contamination. Domo had large total concentrations over the course of 2020 even though it does not have a touristic use but is located in a middle of town inhabited only by local residents. However, it is in the middle of the Leona Vicario community, a town with a population of 7028 people as of the 2020 census, according to the Instituto Nacional de Estadística y Geografía (n.d.). VL and PP, recreational areas, recorded large concentrations during touristic lows. As groundwater flowed from Domo and LL (a limited tourist site with relatively high concentrations) toward the coast, it picked up more contaminants at the recreational site PV. Across the well field, concentrations are very low, showing that incoming waters must dilute the contaminants at the well sties. Yet, concentrations pick up in the recreational site in VL. The well locations in Puerto Morelos had high concentrations in 2020 and reduced concentrations in 2021. While the beach locations, wells, and recreational sites may have higher concentrations due to touristic use and the convergence of inland contaminated water, the concentrations are higher during 2020 than 2021, showing continued pollution although tourists were not as prominent.

The Wilcoxon matched-pairs signed-ranks results further illustrate the effect of residents on the contamination of water sources. The test results upheld the null hypothesis that there was no difference in total concentrations from 2020 to 2021, meaning the sites were just as contaminated during the pandemic as they were during the touristic rebound. The only way contamination concentrations could have been similar is if the residents were major contributors to the sunscreen concentrations.

Governments started to ban and/or regulate the use of sunscreens due to its effects on oceanic ecosystems and people. The most restrictive regulations on sunscreens are from the Republic of Palau, which banned all organic UV-filter sunscreens (Palau National Government Services, 2020). Hawaii banned oxybenzone and octinoxate in 2018, began the process of banning sunscreens with avobenzone and octocrylene in 2021, and proposed a resolution to insist that the Hawaii Department of Land and Natural Resources install mineral sunscreen dispensers at all the beaches, which was in legislative committee at the time of this writing (Hawaii State Legislature, 2022a, 2022b, 2022c). The City of Key West, Florida, banned oxybenzone and octinoxate (City of Key West, 2019) and the U.S. Virgin Islands banned the oxybenzone, octinoxate, and octocrylene (Legislature of the Virgin Islands, 2019). Other locations around the world have banned oxybenzone such as Thailand, Aruba, the Northern Mariana Islands, Bonaire, and the Marshal Islands (Downs et al., 2022).

The state of Quintana Roo does not regulate the use of sunscreens at any water body. Municipalities like Tulum and Solidaridad have instituted restrictions on the type of sunscreen, preferring biodegradable types over others (Casas-Beltrán et al., 2021). In 2019, researchers calculated that between 231 and 313 tons of sunscreen flowed through the aquifer and into the oceanic basins where the Mesoamerican Barrier Reef is located (Casas-Beltrán et al., 2021). This study shows a continued trend of high sunscreen contamination regardless of the presence or absence of tourists. Locals applied copious amounts of sunscreens, more than during the touristic highs, further exposing the natural environment to harmful compounds. Since tourists are returning, the trend will only continue to worsen.

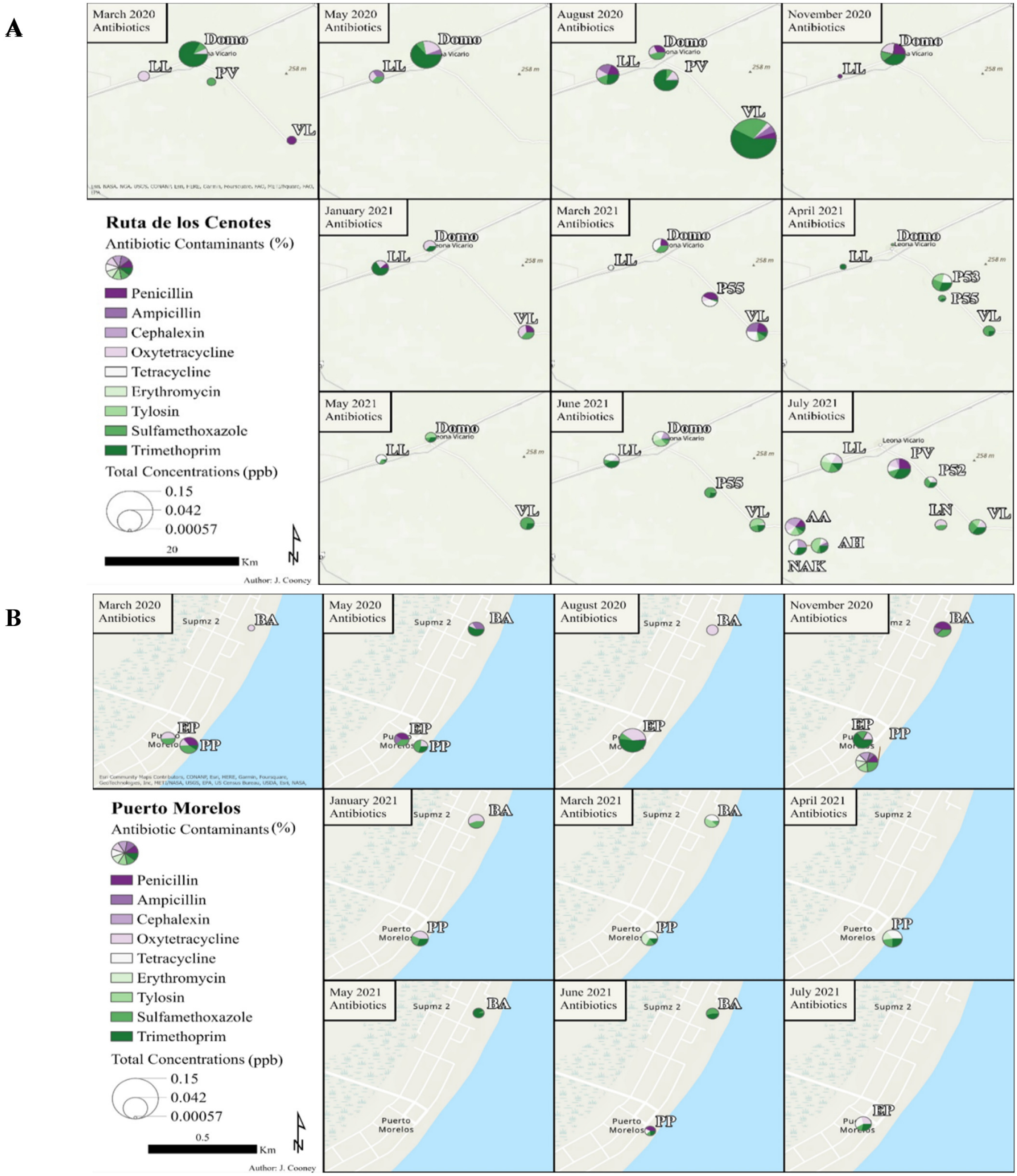

Fig. 5. Antibiotic concentrations from March 2020 to July 2021. (A) Ruta de los Cenotes, (B) Puerto Morelos.

Tourists visiting the beaches and cenotes used a variety of sunscreens that ended up in the water. Compounds such as benzophenone-4, benzophenone-3, octocrylene, octyldimethyl-p-aminobenzoic acid, and 4-methylbenzylidene camphor were not prominent in early groundwater samples because the residents were not using them. As tourism returned to the Riviera Maya, these compounds' concentrations increased. The diversification of sunscreens and antibiotics coincided with the increase of the percentage in hotel room occupation in 2021.

Besides sunscreen as a tracer of human impact on groundwater, antibiotics were also detected in groundwater. The medical community continually advises patients, physicians, and policy makers about the appropriate use of antibiotics and warns of antimicrobial resistance from misuse

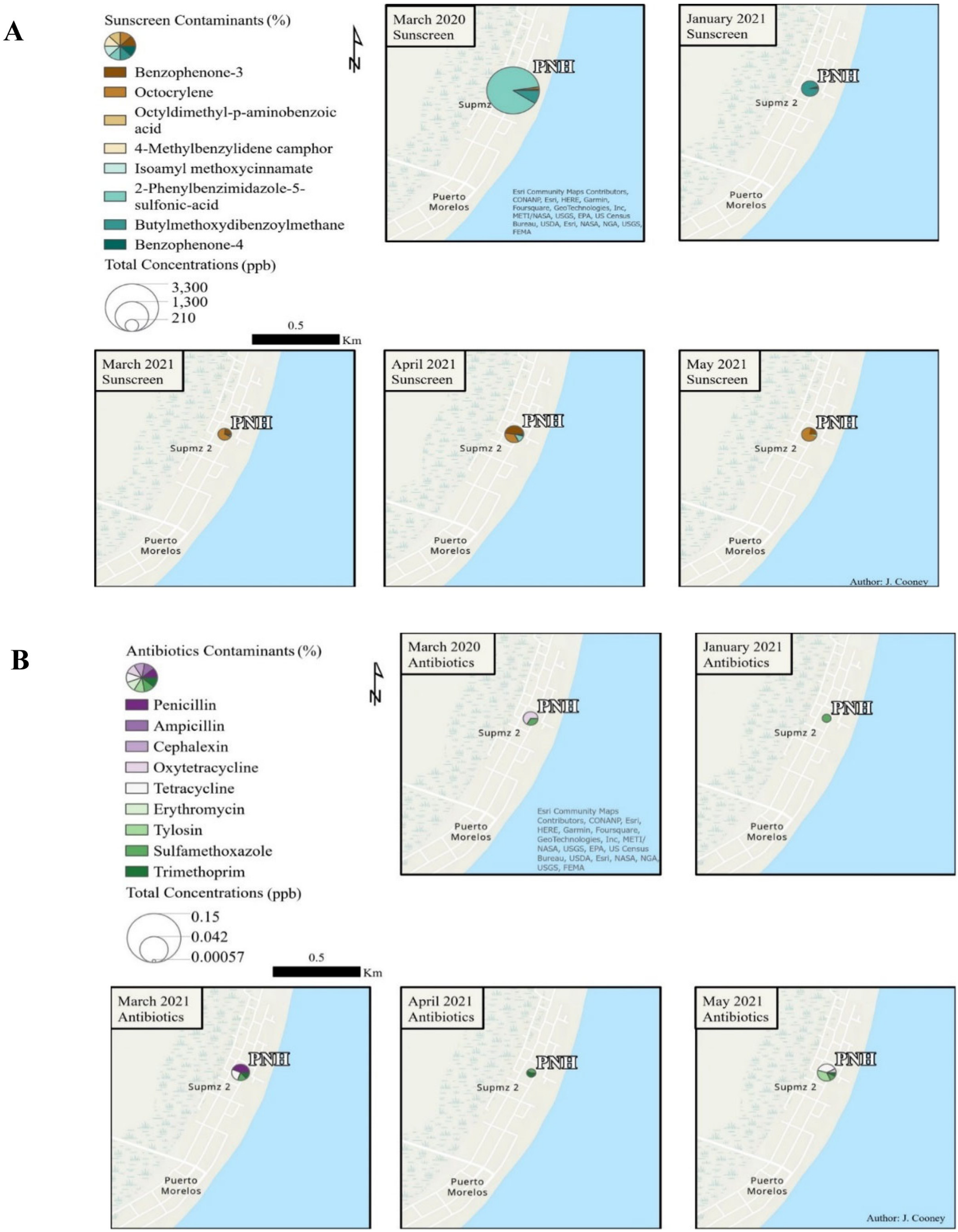

Fig. 6. PNH beach location concentration (ppb) (A) Sunscreens, (B) Antibiotics from March 2020 to May 2021.

(WHO, 2020a, 2020b, 2020c). Patients used to be prescribed a course of antibiotics as a prophylactic or treatment for traveler's diarrhea, a temporary disease resulting from poor water quality and lax disease prevention practices (CDC, 2019). But antibiotic resistance is causing doctors to question the necessity and effectiveness of recommending antibiotic treatments (CDC, 2019; Ericsson and Riddle, 2018; Keystone and Connor, 2017; WHO, 2020a, 2020b, 2020c). However, the perception that antibiotics can treat all types of traveler's diarrhea persists (Doucleff, 2015). Furthermore, human exposure to antibiotics can come from diets in which the food source (i.e., pigs) was given antibiotics like tylosin (Ben et al., 2022; Hu et al., 2022), a drug that increased in this study's samples as tourism increased.

Misconceptions about antibiotics contributed to the use of the drugs as a treatment for COVID-19 (Baracaldo-Santamaría et al., 2022; Pew Charitable Trusts, 2021). The same misconceptions may explain the concentration profile of antibiotics in the groundwater samples in the early months of the pandemic. Haphazard use of antibiotics as prophylactics or treatment for COVID-19 could contribute to the high concentrations in 2020. Because treatment and preventative options were low or nonexistent, people self-medicated with drugs they were familiar with – antibiotics. Hu et al. (2022) attributed the higher levels of antibiotics in their study in China during the COVID-19 pandemic partially to self-medication. Trimethoprim was the highest concentration, although when taken alone, it does not treat respiratory illnesses (see Table S1). Sulfamethoxazole, the second highest concentration, treats respiratory illnesses, but only in conjunction with trimethoprim. After tourists returned, the types of antibiotics found in groundwater treat illnesses more akin to touristic activity in the area. Antibiotics treating respiratory illness were still being used, but other antibiotics for G.I. distress also increased as travelers returned.

Of note was the occurrence of tylosin in the samples. November 2020 was the first occurrence of the veterinary antibiotic, with the highest readings occurring June and July 2021, which were significantly large proportions of contaminant concentrations. Unintentional exposure may account for the increased assortment of antibiotics, including tylosin, detected in the samples. Unsuspecting people can ingest antibiotics used in food-source animals or in insufficiently treated drinking water, thus excreting the drug into sewage systems (Ben et al., 2022; Hu et al., 2022; Wang et al., 2022; Zeng et al., 2020). Both Wang et al. (2022) and Zeng et al. (2020) identified diet as the leading contributor of antibiotic exposure in people in China. Ben et al. (2022) detected antibiotics such as sulfamethoxazole, trimethoprim, tetracycline, oxytetracycline, erythromycin, and tylosin in drinking water, food-source animals, and plant-source foods, which may explain the spike in tylosin during the second half of the study period. Wang et al. (2022) identified the same compounds, except for tylosin, in their study of dietary exposure. Zeng et al. (2020) linked sulfamethoxazole and trimethoprim in human urine to the ingestion of contaminated foods. While Hu et al. (2022) correlated COVID-19 cases and antibiotic use; the authors also attributed the high antibiotic presence in tests to dietary meats.

Tylosin's presence calls into question whether the variety of antibiotics found in groundwater samples during 2021 were a result of medicinal use or something else. Higher numbers of tourists mean more people will consume foods treated with antibiotics. Although the concentrations in food might be low, the number of people consuming and excreting these low concentrations of the drugs can accumulate into a larger concentration in wastewater. An investigation into antibiotics in food sources and groundwater contamination should be performed to understand whether this route is a contributor to the levels reported in this region. However, the food-source exposure need not be from meals consumed in Quintana Roo, but from exposure in the home countries of tourists. Kolokotsa et al. (2021) reported a change in local antimicrobial resistance in water samples when tourists visited the island of Zakynthos. Changes to Quintana Roo's antibiotic contamination profile could also be explained by people excreting antibiotics they have been exposed to outside of the state.

The second aspect of this study was to investigate how sewage disposal practices affect the levels of contamination in Puerto Morelos. Quintana Roo residents complained about the water quality and the lack of adequate infrastructure to manage the influx of sewage and wastewater for years (Rivera Maya News, 2019a; Rivera Maya News 2021a, 2021b). The local and state governments began a project to connect drainage systems to wastewater treatment plants instead of the septic tanks (Riviera Maya News, 2019b, 2019c, 2019d). It is unclear how many locations have been connected to the new system. The Riviera Maya News (2019b) article dated September 2019 stated that Puerto Morelos was 90 % connected to the system, but the article dated October 2019 claimed that the connection was only 70 % (Riviera Maya News, 2019c).

The PNH location, separated from the rest of the dataset to investigate this question, showed a major decrease in contamination from sunscreens after March 2021. More research would have to be done to determine the connection date of this and other locations to further understand the correlation. Based on the total concentrations of sunscreens and antibiotics, the connection project reduced the amount of contaminants in well water at PNH. The results of the new sewage system are promising, yet people are still waiting for drainage connections and must rely on leaky septic systems and/or dumping into cenotes or pits for waste disposal. Therefore, contamination will continue until all septic systems are remediated and opportunities for proper waste disposal are expanded to other areas.

6. Conclusion

In conclusion, the goal of this study was to assess how tourist activities affect groundwater resources in a coastal community by examining the absence of tourism during the COVID-19 pandemic and the subsequent return of tourists. The results of this study found that while tourism may be responsible for the increase in sunscreen and antibiotic diversity in groundwater, it is not the sole reason for groundwater contamination in the Riviera Maya. Local residents are a major contributor of pollution in the water supply. The continual contamination of groundwater by sunscreen and antibiotics in the absence of tourists shows how much residents contributed to the overall pollution of the water supply.

Research on the human effects on groundwater in the region must continue to fully realize the impact. Conceptualizing resident contributions to groundwater pollution has been difficult in the past because the sheer number of tourists overshadowed the local population throughout the year despite seasonal fluctuations. The COVID-19 pandemic created a rare opportunity to describe local impacts on water quality in a tourism-dependent region. Improved local infrastructures can effectively manage the concentrations of pollutants in groundwater from residents as well as visitors.

CRediT authorship contribution statement

Jacqueline Cooney: Writing – original draft, Formal analysis, Investigation, Visualization. **Melissa Lenczewski:** Supervision, Funding acquisition, Writing – review & editing, Resources. **Rosa Maria Leal-Bautista:** Writing – review & editing, Conceptualization, Resources. **Kevin Tucker:** Writing – review & editing, Methodology, Resources. **Megan Davis:** Methodology, Investigation. **Jasmine Rodriguez:** Investigation, Methodology.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164820.

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