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Evaluation of arsenic effects on *Paracyclops novenarius* Reid, 1987: a cyclopoid copepod in central-north of Mexico

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Abstract
Description and morphological analysis of copepods inhabiting a water body with high arsenic concentrations (32.79 to 62.29 mg L^{-1}) were performed to identify some effect on the development of individuals due to the arsenic concentrations. Detailed morphology of prosomal and urosomal appendages along the development of the specimens was considered. The results showed that the freshwater copepod *Paracyclops novenarius* Reid, 1987 inhabits this water body, and previously, it was recorded as *Paracyclops chiltoni* (Thomson GM, 1882) on this site. Moreover, this becomes the first record of *P. novenarius* in Mexico. Morphological analysis showed a normal and stable development along the different instars, different arsenic concentrations in the media, and different sampled dates between the analyzed specimens, suggesting that the high arsenic concentrations do not affect the morphology of *P. novenarius*, including all its development and adult instars, which differs from other copepods and other groups such as *Cladocera* and *Rotifera*, where morphological changes due to metals and metalloids have been observed but in low concentrations of these elements. The results of this study contribute to the existing reports of the genus *Paracyclops* (Claus 1893) in Mexico and could provide information for environmental impact assessments on aquatic systems.

Keywords Arsenic · Cyclopoida · Ecological parameters · Mexico · Taxonomy · Water pollution

Introduction

Arsenic (As) is a metalloid element that occurs in the environment in both organic and inorganic compounds, constituting approximately 5×10^{-4}% of the earth's crust (Caussy and Priest 2008; Bundschuh et al. 2008). In general, As levels in water are lower in surface waters (seas, rivers, and lakes) and higher in groundwater, especially in areas with deposits of volcanic rock or minerals rich in As (Bundschuh et al. 2008). Nevertheless, anthropogenic activities such as mining, metallurgical processes, fossil fuel combustion, and pesticide use increase its concentrations (Ravenscroft et al. 2009; Gutiérrez and Gagneten 2011).

This element is recognized as one of the world's most significant environmental hazards due to its toxicity (Ravenscroft et al. 2009). The extension and the geological complexity of Mexico lead to a variation of the contents and origins of arsenic in groundwater between different areas, mostly in the central and northern part such as Hermosillo, Yaqui Valley, Chihuahua Comarca Lagunera, Zimapán, and San Luis Potosí (Armienta et al. 2008; Navarro-Espinoza et al. 2021).

For instance, in Matehuala, San Luis Potosi, high concentrations of arsenic (up to 158 mg L^{-1}) have been reported due to metallurgical wastes in freshwater (Razo et al. 2004; Martínez-Villegas et al. 2013; Ruíz-Huerta et al. 2017; Mendoza-Chávez et al. 2021). The values greatly exceeded the Mexican guidelines for the conservation of aquatic life (0.2 mg L^{-1}) and water quality for human use and consumption (0.05 mg L^{-1}) as well as international guidelines (EPA 1994; DOF 1994, 1998).

The input of this element to freshwater systems would lead to significant alterations in physical-chemistry conditions and generate multiple impacts in the aquatic biodiversity; for example, some arsenic compounds dissolve

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in water and some aquatic organisms accumulate them in the form of organic arsenic (Caumette et al. 2011; Moreira et al. 2016). In this sense, a critical component to understand better these impacts is copepods, which belong to the group of zooplankton microcrustaceans and make up an important part of the biomass of freshwater ecosystems (Williamson and Reid 2001; González et al. 2011; Brandorff 2012; Gómez-Márquez et al. 2013; Cervantes-Martínez and Gutiérrez-Aguirre 2015).

In the world, 14,000 species of copepods are known, of which 3000 are freshwater species (Suárez-Morales et al. 2020); their high sensitivity to alterations in physical and chemical characteristics into the environment make them suitable for use as bioindicators of metal and metalloids contamination (Galassi et al. 2009; Gutiérrez et al. 2010; Gutiérrez and Gagneten 2011; Gutierrez et al. 2012; Villagran et al. 2019).

The response of these organisms could include alterations in reproduction, species richness, biomass, and behavior (Gagneten and Paggi 2009; Hwang et al. 2010; Mohammed et al. 2010; Gutierrez et al. 2012; Dahms et al. 2016) as well as morphological anomalies (Krupa 2005; Krupa et al. 2020; Melo et al. 2021).

Knowing how copepods respond to environmental stressors becomes essential to understand better the toxic process in the long term and their suitability to consider them as potential indicators of aquatic ecosystems health, acquiring great relevance from an ecological and environmental perspective.

In this work, we reported for the first time in Mexico the freshwater copepod *Paracyclops novenarius* Reid, 1987 (misidentified as *Paracyclops chiltoni* Thomson GM, 1883 by Mendoza-Chávez et al. 2021) inhabiting water polluted by arsenic. A detailed analysis of morphology was carried out to identify possible morphological anomalies in the life cycle of this species, bearing in mind the number of collected specimens in one freshwater system within two different climatic seasons (rainy and dry). Moreover, the probable mechanisms that allow *P. novenarius* to live are discussed.

Material and methods

The study area is in the city of Matehuala, San Luis Potosi, Mexico, and corresponds to a shallow water body (< 2 m depth) known as "Club de Tiro," which is part of an artificial complex of water contaminated with arsenic (Razo et al. 2004; Martínez-Villegas et al. 2013) (Fig. 1). Recent research showed that arsenic concentrations ranged from 32.79 to 62.29 mg L^{-1} since the year 2015 (Mendoza-Chávez et al. 2021). The climate is arid; its annual average temperature is 19.3 °C, with an average yearly rainfall of 450 mm. The predominant soil type is calcic to gypsic xerosol with a gradual increment of gypsum towards the center (Razo et al. 2004; CEFIM 2016) (for more details of the study site, see Mendoza-Chávez et al. 2021).

Biological samples were collected with a plankton net of 50 µm mesh by filtering a known volume and were fixed with 96% ethanol (Cervantes-Martínez and Gutiérrez-Aguirre 2015). Fieldwork was carried out in two seasons registered by INEGI (2002) (rainy = August 2017 and dry = December 2017).

To identify the species and some effect on the development of individuals due to the arsenic concentration, adult females and males of the collected copepods were analyzed with a JEOL-SM-6010 microscope. Nauplii and copepodites were also included in this analysis. Ten organisms of each development stage were randomly taken for the SEM analysis; these were taken from those most numerous isolated (Table 1).

Once with the SEM analysis, the morphological analysis was carried out as follows: electron microscopy observations were compared with fresh organisms in light microscopy Nikon Eclipse 50i, that is, 10% of each isolated stage, chosen at random when the number of these was greater than 10. When there were less than 10 organisms, they were compared entirely.

Procedures for material preservation, preparation, and conservation were made according to Suárez-Morales et al. (2020); biological material was deposited in the Reference Collection of Zooplankton of ECOSUR at Chetumal (ECOCH-Z-10508).

Detailed morphology of prosomal and urosomal appendages along the development of the specimens was considered. The terminology for the armament of each appendage followed Huys and Boxshall (1991) and Karaytug and Boxshall (1999): antennule (= A1), antenna (= A2), mandible, maxillule, maxilla, maxilliped (= Md, Mxl, Mx, Mxp, respectively), first to sixth legs (= P1 to P6), Exp (= appendage, exopodal limb), Enp (= appendage, endopodal limb), first to sixth naupliar stages (= NI to NVI), and first to sixth copepodite stages (= CI to CVI).

Finally, the probable biological strategies that allow the survival of the copepods that inhabit the surveyed system were discussed, based upon the results.

Results

Only one species of *Copepoda* was present in the analyzed system, which previously was identified as *Paracyclops chiltoni* Thomson, 1883 (see Mendoza-Chávez et al. 2021); however, after the actual analysis, the observed specimens were synonymized with *P. novenarius*, described by Reid (1987) and re-described by Karaytug and Boxshall (1998a). Normal and stable development was observed along the

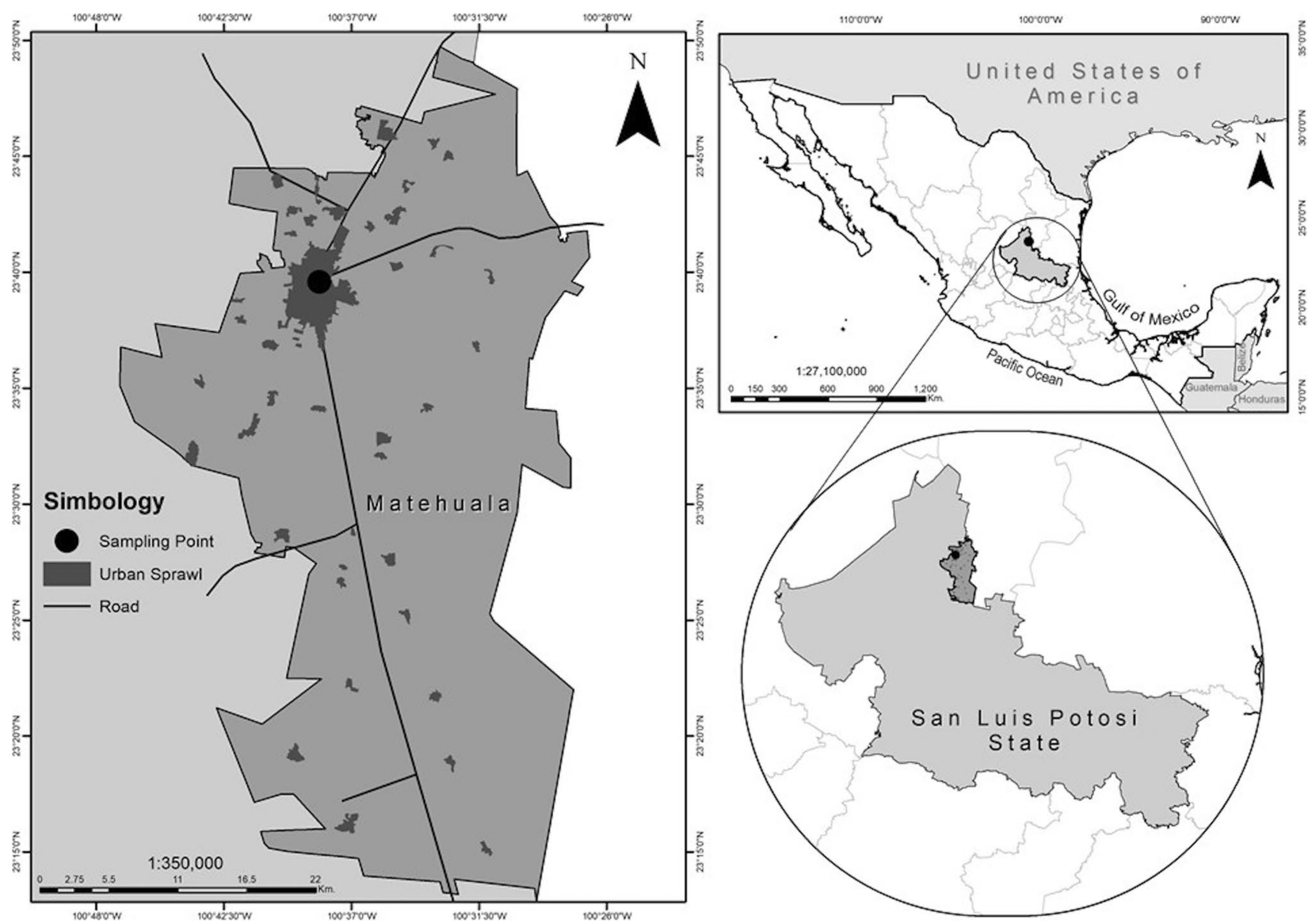


Fig. 1 Location of the study area in Matehuala, San Luis Potosi

Table 1 Number of total organisms isolated for each sample

Collection date	Development stage				*Arsenic (mg L^{-1})
	Female	Male	Copepodite	Nauplii	
17/08/2017 (rainy)	103	7	102	30	55.11
17/12/2017 (dry)	446	21	146	151	62.29

*Concentration reported byMendoza-Chávez et al. (2021)

different instars, different arsenic concentrations in the site, and different sampled campaigns between all the analyzed specimens (Figs. 2, 3, 4, and 5). All naupliar stages with the typical labrum, A1, A2, Md, and one couple of spinulose caudal seta on each side of the body were present in Nauplii II to VI (Fig. 2A–C). Antennule armed with sabre-shaped masticatory process; the maxillule is differentiated as on setose and distal lobe, and first leg bud is differentiated in Nauplius VI (Fig. 2A–C).

As typically, the outer lateral furcal seta (seta III) is placed more proximally during Copepodite I and lateral furcal seta (II) is placed inwards, whereas dorsal seta (VII) is placed near its final place when the copepodite grows to instar V (Figs. 2D–G and 3A, B). Six antennular segments, as well as the first P1–P3, were developed during CV (Fig. 3C–D). A highly differentiated and geniculated A1 was observed in CVI (Fig. 3E), as well as three-segmented Enp and Exp in P4, and elements of P6 were longer than in adults (Fig. 3F).

For adults (Figs. 4 and 5), morphological features of the observed specimens correspond to *P. novenarius*, such as the number of antennal segments, and antennal armature in females (8 s, 12 s, 6 s, 5 s, 2 s + ae, 2 s, 2 s + ae, 7 s + ae) and males (8 s + ae, 4 s, 2 s, 2 s + ae, 2 s, 2 s, 2 s, 2 s, 2 s + ae, 2 s, 2 s, 2 s, 6 s, 3 s + ae, 11 s + ae). All these features were stable in all the observed specimens of all collections.

Ornamentation of buccal and thoracic appendages corresponds to *Paracyclops novenarius*, including the presence of large setules on coxal, distal margin of P1–P3 (on caudal view: Fig. 5C, B, G), and the absence of ornamentation in this distal margin on P4 (at least not identifiable with light microscopy) (Fig. 5H). Furthermore, features related to sexual dimorphisms, such as the ornamentation of antennal basis, Enp3P1, and Enp3P3, also correspond with *P. novenarius*.

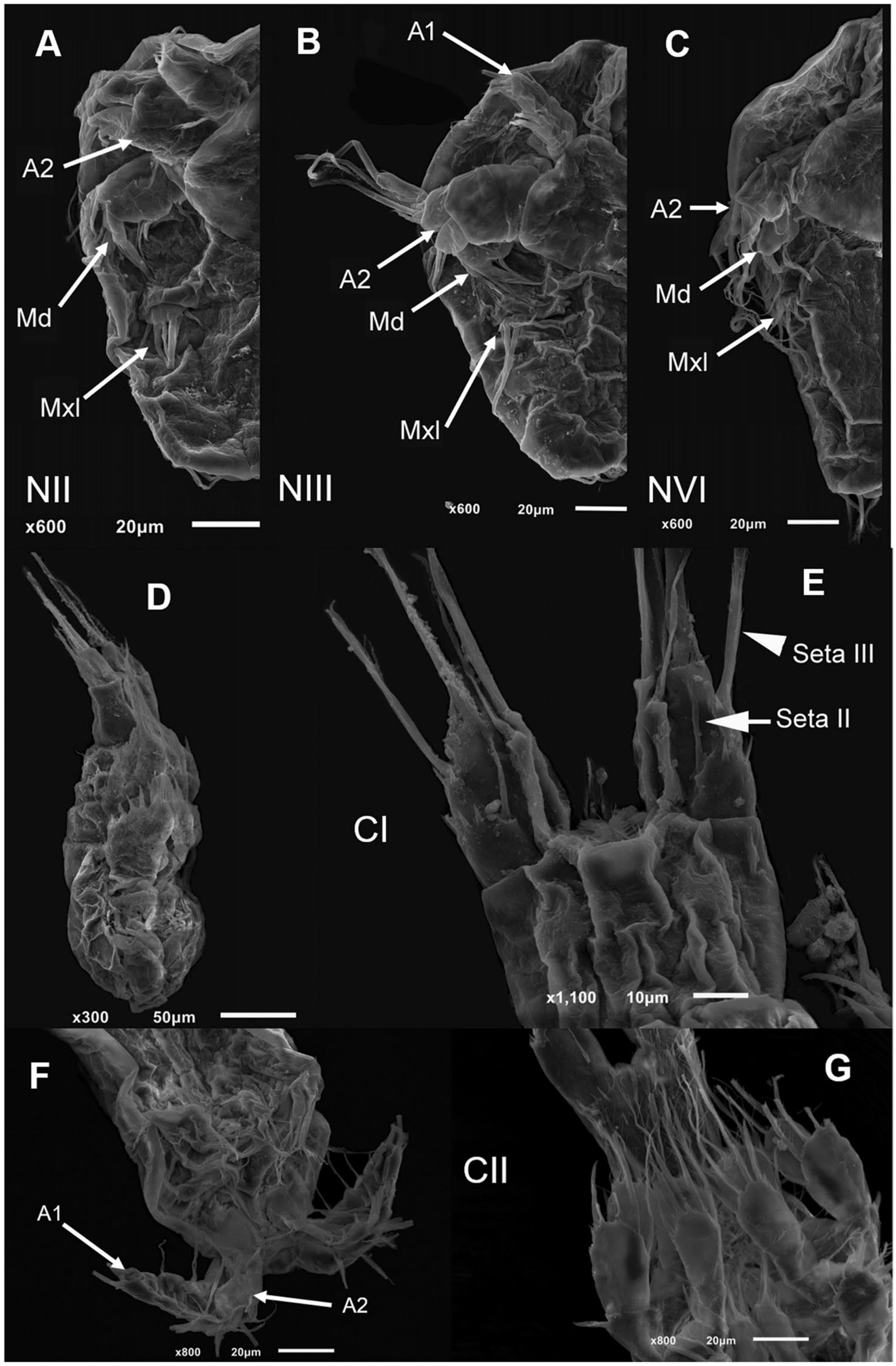


Fig. 2 *Paracyclops novenarius*, immature stages (sampled collection 2017). **A**–**C** Nauplii II–IV. D) Copepodite CI, lateral. **E**) CI, anal somite, and caudal rami, ventral. **F**) Copepodite CII, prosome ventral, **G**) CII, prosome, and urosome, ventral

Discussion

In the world, around 30 species and subspecies of the genus *Paracyclops* Claus 1893 have been recorded in different types of freshwater habitats, distributed in temperate-cold latitudes and in tropical areas in which the genus tends to present more species (Karaytug and Boxshall 1998a, b; Karaytug et al. 1998; Mercado-Salas and Suárez-Morales 2009).

Before this study, four species of *Paracyclops* have been inventoried in Mexico: *Paracyclops poppei* (Rehberg, 1880), *Paracyclops hirsutus* Mercado-Salas & Suárez-Morales 2009, *Paracyclops fimbriatus* (Fischer, 1853), and *Paracyclops chiltoni* (Thomson GM, 1883) (Mercado-Salas and

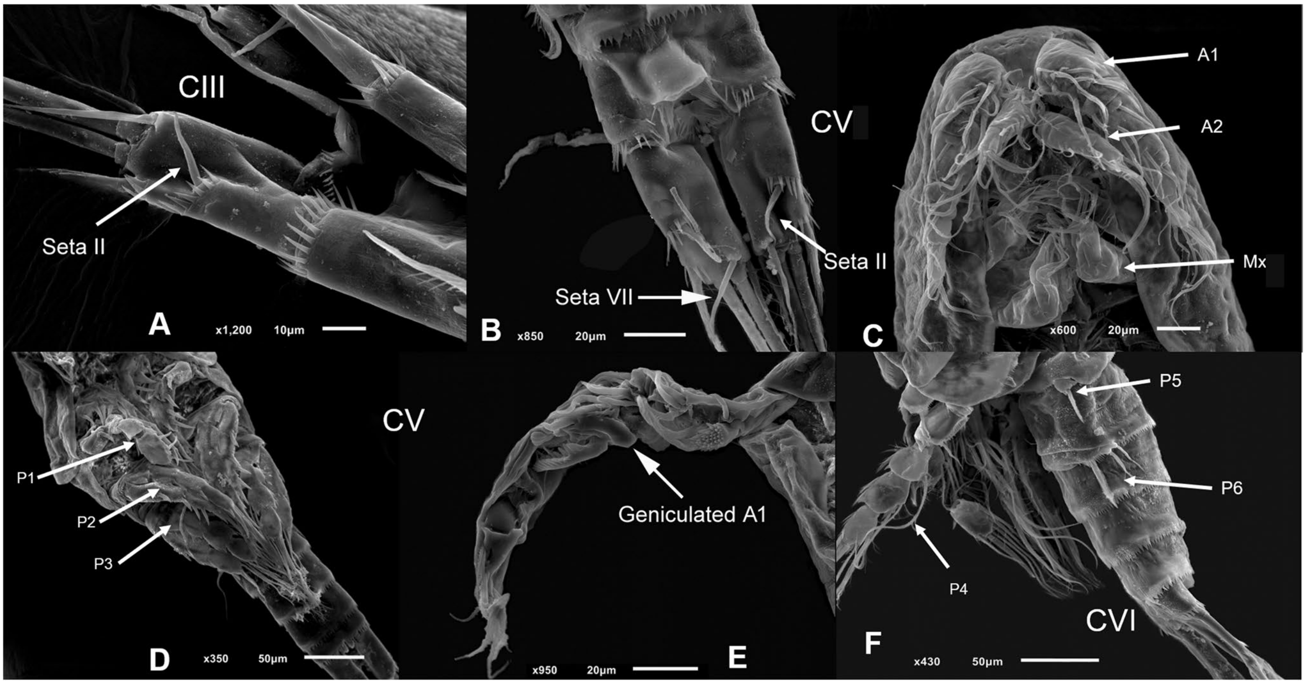


Fig. 3 *Paracyclops novenarius*, immature stages (sampled collection 2017). **A** Copepodite III, caudal rami. **B** Copepodite V, anal somite, and caudal rami. **C** Copepodite V, prosome, ventral. **D** Copepodite V, P1–P3. **E** Copepodite V, A1. **F** Copepodite VI, lateral

Suárez-Morales 2009, 2012; Suárez-Morales 2020). At the study site, previous work reported the presence of the species *P. chiltoni* (Mendoza-Chávez et al. 2021); however, in this work, the detailed morphological analysis by scanning and light microscopy determined that it is *Paracyclops novenarius*; thus, this is the first record in the country.

P. novenarius was reported for the first time in Colombia by Reid (1987), later by Gaviria (1994), and Gaviria and Aranguren (2007), inhabiting artificial asbestos containers. This material is well known to be carcinogenic (Barrera et al. 2010). Asbestos is composed of silicate fibers; the mineral is obtained in open quarries or shallow mines (Castellano-Alvarado et al. 1960), and according to its physical characteristics, it can be composed of SiO_4^-. In addition, in the region where *P. novenarius* was registered, heavy metals such as Cu, Cr, Ni, and Zn have been reported, which exceed the contamination limits established by the EPA (Collazos-Santos 2014).

At the study site, this species is living in an environment that significantly exceeds the concentration of arsenic considered lethal for zooplankton (3 mg L^{-1}) (Chen et al. 1999) and could be recognized as an extremophile organism due to the ability to thrive in this habitat which for other organisms might be intolerably hostile or even lethal (Rampelotto 2013; Mendoza-Chávez et al. 2021). Laboratory studies have shown that metals and metalloids could affect copepods in a minor way compared to cladocerans and rotifers because these are relatively more tolerant to toxic action (Gagneten and Paggi 2009). According to Caumette et al. (2011), copepods of the genus *Cyclops* bioaccumulate arsenic between 7 and 340 mg kg^{-1}. At the study site, Mendoza-Chávez et al. (2021) suggest that arsenic bioaccumulates 9.6 ± 5.4 mg kg^{-1} in the digestive tract of the copepod, allowing it to survive in that environment.

The anamorphic development of *P. novenarius* during its naupliar, copepodid, and adult instars observed in the freshwater analyzed system was typical of the cyclopoids, even with the extremely high and seasonally variable arsenic concentration in the studied population. Some differences were found in comparison with additional freshwater *Cyclopidae* species whose development is known (Dahms and Fernando 1992; Ferrari 2000), for instance, the number of added segments on each appendage or the number of setulae on each appendage segment, but this appears to be more related to the recognizable morphological differences between species, even at the earliest developmental stages (Suárez-Morales et al. 2007), than the effect of the contaminant (arsenic) on the *P. novenarius* morphology. Body length reported by Mendoza-Chávez et al. (2021) were within the ranges (570–880 µm for females and 540–640 µm for males) reported by Reid (1987) for *P. novenarius* in the type locality.

The above differs from other results reported for *Cladocera*, *Rotifera*, and *Copepoda* groups, where morphological changes have been observed and related to diverse pollutant agents (Table 2). But to our knowledge, no morphological

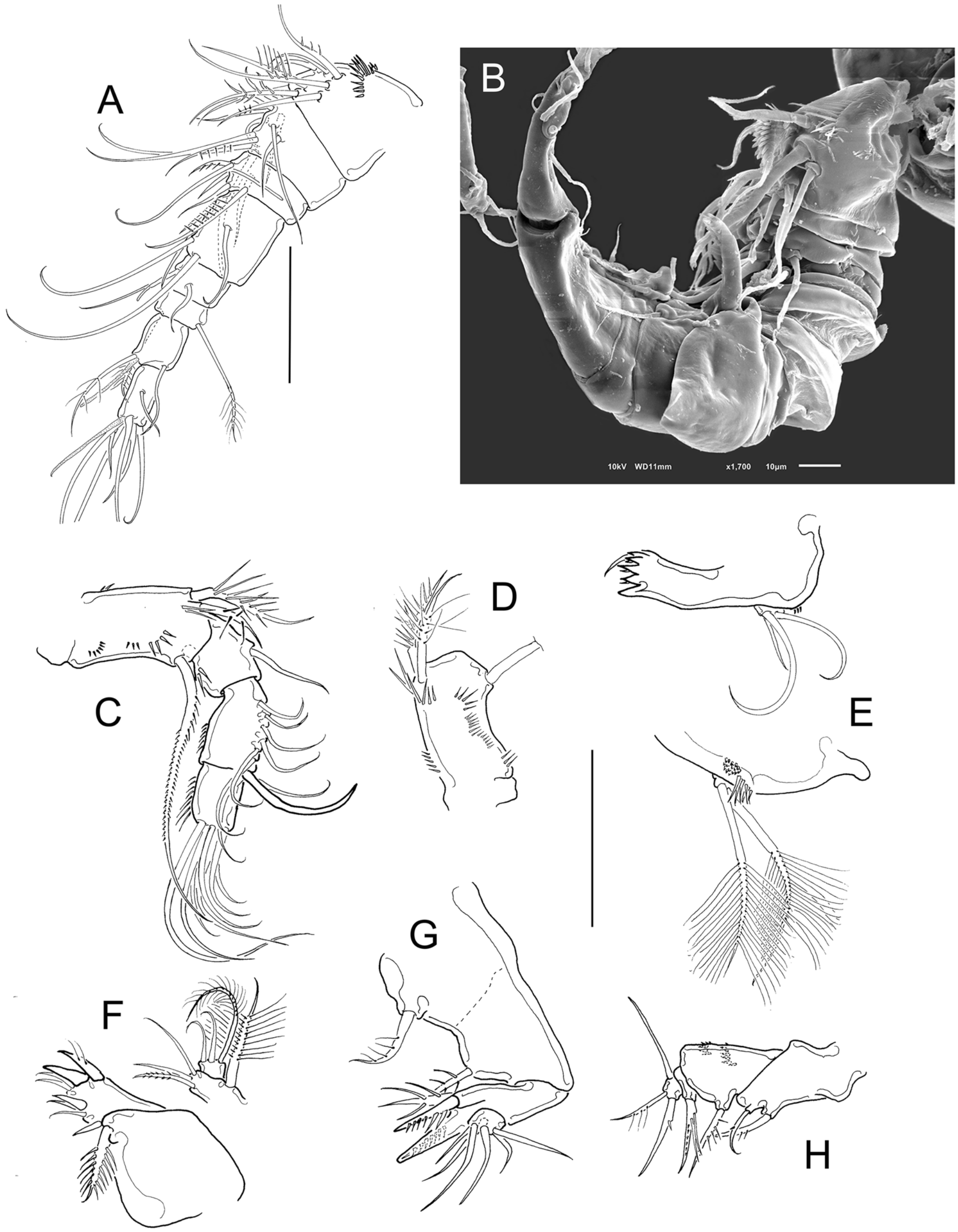


Fig. 4 *Paracyclops novenarius*, adult. **A** Antennule, female. **B** Antennule, male. **C** Antenna, female. **D** Antenna, basis, male. **E** Mandible, posterior, anterior view separated. **F** Maxillule. **G** Maxilla. **H** Maxilliped

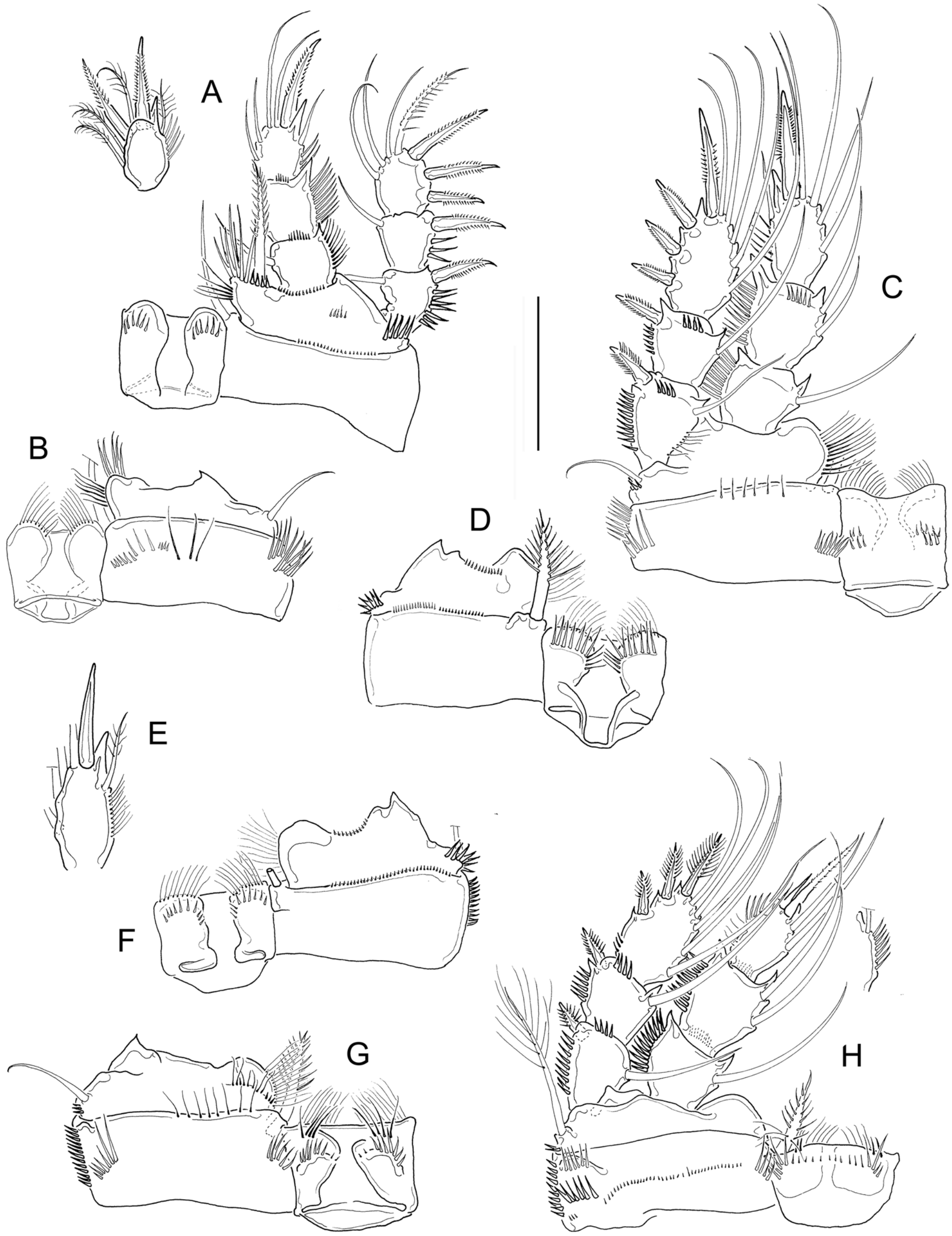
effect during the development of freshwater copepods has been recorded in the presence of extremely high concentrations of arsenic such as in this site.

On the other hand, in the presence of metals and metalloids, laboratory tests showed acute and subchronic toxicity in copepods (Wong and Pak 2004; Hose et al. 2016) and a decrease or growth in the population of aquatic invertebrates (Zou 2010; Alvarado-Flores 2014). Moreover, affectations in the physiological functions such as feeding and swimming (Sobrino-Figueroa et al. 2020), suggesting that similarly, arsenic could act as an endocrine disruptor that affects the reproduction of aquatic organisms. For instance, endocrine disruptors could increase reproduction rates on freshwater rotifers (Alvarado-Flores et al. 2015).

This study verified that the analyzed copepods did not present morphological modifications in the integument during their entire development stages. Neither was changes observed in the shape and position of the structures involved in chemoreception and/or reproduction (such as setae, setules, aesthethascs, tegument ornamentation, fifth legs, or seminal receptacles) of the organisms observed.

However, although there is no effect on the morphology of *P. novenarius*, the results suggest an effect on the population numbers of the copepod exposed to high concentrations of arsenic. Mendoza-Chávez et al. (2021) reported a ratio of females and males (F:M) where the number of males in the analyzed population tends to be extremely low (21:1 and 14:11 for the dry and rainy season, respectively). A similar

Fig. 5 *Paracyclops novenarius*, adult. **A** First leg, frontal, female; Enp3P1 separated, male. **B** First leg, caudal. **C** Second leg, caudal. **D** Second leg, frontal. **E** Enp3P3, male. **F** Third leg, frontal. **G** Third leg, caudal. **H** Fourth leg, caudal



result was reported when rotifer *Brachionus calyciflorus* was exposed to high concentrations of arsenic under laboratory conditions because, similarly, the number of males tends to decrease or disappear (Alvarado-Flores 2014).

In general, abundances described by Mendoza-Chávez et al. (2021) are low in comparison with other copepods inhabiting other aquatic systems without pollutant agents (up to 1,182 ind L^{-1}) (Gerten and Adrian 2002; Mitsuka and Henry 2002; Cervantes-Martínez et al. 2005; Sarma et al. 2011; Gómez-Márquez et al. 2013; Cervantes-Martínez and Gutiérrez-Aguirre 2015); however, the abundances were similar to the values reported by Gagneten and Paggi (2009) inhabiting water polluted by heavy metals (0.03–1.84 ind L^{-1}). Therefore, in Club de Tiro, the arsenic could act as an endocrine disruptor, whose most notable effect is observed in reducing its population and the lower abundance of males in an organism with strict sexual reproduction.

Nevertheless, questions and hypotheses remain to be addressed:

- The arsenic concentration in the water is extreme that the threshold is reached at which the metalloid ceases to be toxic, as reported by Babula et al. (2008).
- The established population of *P. novenarius* in this site has an adaptive response that increases the organism's

Table 2 Studies of morphological changes of zooplankton species related to pollutant agents

Group	Species	Morphological change	Pollutant agent	Source
Cladocera	*Daphnia magna* Straus, 1820	Carapace deformation Alterations in embryo development	Pb Cd, Zn	Araujo et al. (2019) Pérez and Hoang (2017)
	Daphnia gessneri Hernst, 1967 *Ceriodaphnia silvestrii* Daday, 1902 *Bosmina longirostris* (O.F. Müller, 1975) *Bosmina tubicen* Brehm, 1953 *Chydorus pubescens* Sars, 1991	Deformation of the rostrum and a folded tail spine, increased length of intestine and size of intestinal loop, intestine prolapse	Pesticides	Melo et al. (2017)
Copepoda	*Acanthocyclops* sp. *Cyclops* sp.	Malformations in the furcal rami, setae and abdomen	Zn, Cu, Cd, Pb	Krupa (2005)
	Achanthocyclops robustus (Sars GO, 1863) *Cyclops vicinus* Uljanin, 1875 *Acanthocyclops trajani* Mirabdullayev & Defaye, 2004	Left branch misshapen Shortening of one of the furcal rami, as well as shortening and deformation of the furcal setae	Wastewater, heavy metals Cd, Cr, Cu, Ni, Pb	Krupa (2007) Krupa et al. (2020)
Rotifera	*Brachionus calyciflorus* Pallas, 1776 *Philodina cf roseola* *Brachionus plicatilis* (Müller, 1786)	Reduction in the body size and morphometrical characteristics Modification of the ciliated corona, deformation of lorica Deformations in the foot, head, and the middle part of the trunk Deformation of the cilia of the cingulum, foot retraction, toes swollen, corrugation of the integumental surface	Cd, Cu Coal ash, Al, As, B, Cr, Mo, Sb, Se and V Fungicides Cd Cd, Cu	Gama-Flores et al. (2017) Xue et al. (2017) Alvarado-Flores et al. (2015) Pérez-Yáñez et al. (2019) Elkhodary and Elsayed (2011)

resistance to severe stress, reaching the state of hormesis defined by Calabrese (2008).

- The organic arsenic compounds accumulate in a more significant proportion than the inorganic ones in *P. novenarius*' body, allowing the population to be established.
- The hydrogeochemical conditions of the site affect the arsenic toxicity, as reported in other studies for metals and metalloids (Schubauer-Berigan et al. 1993; Borgmann et al. 2005; Hall et al. 2008; Arnold et al. 2010).

Further studies are required due to the necessity to obtain more sensitive and representative indicators of pollution of each region. The study of copepods, including their morphological and ecological aspects, is essential to evaluate the toxic effects of pollutants and lays the basis for considering them as potential indicators of freshwater system's health.

Conclusions

In this study, we reported for the first time in central-north Mexico the freshwater copepod *P. novenarius* inhabiting a water system with highly arsenic concentrations. The morphological analysis also concludes that arsenic does not affect the morphology in all development stages but probably acts as an endocrine disruptor based upon the low recorded abundances. Further studies are required to know more specific effects and mechanisms of action of arsenic on the life cycle of *P. novenarius*. Finally, knowing the probable impact of this metalloid on ecological characteristics and detailed morphology of plankton in a region recognized for high arsenic concentration in its aquifers could lay the basis for using regional fauna for health analysis of continental aquatic systems in the region.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by JLUC, ACM, and MAGA. The first draft of the manuscript was written by JLUC and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The authors declare that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval and consent to participate We collected from several freshwater ecosystems in Mexico. However, Mexican laws do not protect Zooplankton; thus, no specific permits for this type of field study are needed.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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UQROO-CA-26 - Manejo y Conservación de Recursos Naturales Acuáticos

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Reseña histórica de los ciclones tropicales en el Estado de Guerrero, México (1951-2019)

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Universidad Autónoma del Estado de Quintana Roo

Introducción

El Estado de Guerrero se localiza en las costas del Pacífico suroccidental de la república mexicana; por su ubicación el territorio estatal y, en particular, sus zonas costeras son susceptibles al embate de ciclones tropicales durante los meses de junio a noviembre —temporada de huracanes—, donde la mayor actividad promedio se registra entre los meses de agosto a septiembre. Esta exposición a los efectos asociados a los meteoros, particularmente las lluvias y vientos, de acuerdo con Solow (2017) y Van de Pol *et al* (2017), cobra particular relevancia dado que pueden derivar en grandes costos económicos para la población como consecuencia de las posibles afectaciones a la infraestructura, medios de producción y pérdida de vidas humanas.

Ejemplo de lo anterior son los trabajos publicados por diversos autores en los que se destacan y analizan los efectos y consecuencias de los huracanes *Paulina* [1997] (Villegas-Romero *et al.,* 2009; Ramos *et al.,* 2015; Rodríguez Esteves, 2017), *Ingrid* [2013] (Aviña Vega *et al.,* 2018), *Max* [2017] (Bedolla Solano *et al.,* 2021) y las tormentas tropicales *Henriette* [2007] (Palacios Ortega *et al.,* 2015) y *Manuel* [2013] (Rodríguez Esteves, 2017; Aviña Vega *et al.,* 2018), fenómenos que desencadenaron procesos de remoción en masa e inundaciones que provocaron la pérdida de vidas humanas y daños considerables en la infraestructura y en los sistemas socioecológicos de la región.

Durante el período comprendido entre los años 1951 y 2019 se reportó la formación de 1,535 sistemas ciclónicos en el Pacífico nororiental (IBTrACS, 2019), de los cuales el 14% (208) impactaron el territorio nacional, y de los cuales 104 lo hicieron por las costas del suroccidente del país.

Dicho lo anterior, para el presente estudio se plantearon como preguntas de investigación, el identificar el número de ciclones que impactaron el Estado de Guerrero en el período 1951-2019 y la caracterización de los ciclones como eventos en categoría de extremos, en función de la rareza de su ocurrencia —raros, muy raros y extremadamente raros—, tomando como base los criterios de la Organización Meteorológica Mundial (WMO, 2018).

La caracterización se realizó a partir de las variables de análisis "velocidad máxima de vientos sostenidos" y "mínima presión atmosférica", mediante el modelo estadístico "excedente a un umbral relativo (*exceeding a relative threshold)*" (WMO, 2018) y los umbrales de referencia 10.0 y 90.0; 1.0 y 99.0; y 1 y 99.9 percentiles (Sánchez-Rivera *et al.,* 2021).

Ciclones tropicales

Los ciclones tropicales son fenómenos hidrometeorológicos representados por "una circulación atmosférica cerrada que gira en sentido contrario a las manecillas del reloj en el hemisferio norte y en sentido horario en el hemisferio sur" (NHC, 2019). Estos fenómenos se caracterizan por ser grandes masas de aire cálido y húmedo con intensos vientos y abundantes precipitaciones alrededor de una zona de baja presión (Rosengaus-Moshinsky *et al.,* 2002), los cuales pueden representar una amenaza para las poblaciones y los sistemas socioecológicos de las zonas costeras del país.

Para comprender la dinámica y los patrones que permitan explicar la ocurrencia de ciclones tropicales, diversos autores —entre los que destacan Holland y Bruyère (2014) y Doval, Pérez, Acosta y Rodríguez (2013)— han realizado estudios en los que correlacionan diversas variables, como las siguientes: la temperatura de la superficie oceánica, la actividad de las manchas solares y ENOS (El Niño-Oscilación del Sur).

Eventos extremos

En cuanto a la caracterización de los eventos perturbadores en categoría de extremos, ésta resulta compleja, debido a que no existe un consenso en cuanto a su definición. Stephenson (2008) propone que los ciclones categorizados como extremos serían aquéllos cuya ocurrencia es "rara", con efectos "severos" y "graves", donde "raro" queda definido como aquellos eventos con baja probabilidad de ocurrencia. La WMO (2018) establece que los eventos considerados como "raros", serían aquéllos que superan los percentiles 90 y 95, mientras que los considerados como "muy raros" excederían el rango de 1 y 99 o superiores. Otros autores como Décamps (2008) proponen que los eventos en categoría de extremos serían aquéllos que exceden algún tipo de límite en función de su magnitud, duración y frecuencia.

En la literatura científica no se encontró una definición única y consensuada para definir y clasificar eventos hidrometeorológicos en categoría de extremos. Entre los principales métodos y técnicas identificadas destacan los siguientes: *a*) Pico por encima del umbral (IPCC, 2012); *b*) Teoría del valor extremo (Tiago de Oliveira, 1986); *c*) Excedente a un umbral relativo (IPCC, 2014); *d*) Excedente a un umbral y un período de retorno (WMO, 2018); y *e*) Efectividad: eventos que desencadenan un desastre o emergencia (IPCC, 2014) y que puede ocasionar la pérdida de vidas, lesiones, etc. (WMO, 2018).

Si bien, existen diversas propuestas para categorizar los eventos como extremos, en el caso particular de los ciclones tropicales, la mayoría de los estudios consultados se centran en la clasificación en términos de la "escala Saffir-Simpson —S.S.—", la cual fue desarrollada por los ingenieros Herb Saffir y Bob Simpson, y que toma como base la intensidad de los vientos máximos sostenidos (Schott *et al.,* 2012). Esta escala indica los probables daños materiales que los vientos pudieran provocar y agrupa a los huracanes en cinco (5) categorías en función del aumento de la velocidad de los vientos, sin embargo, esta escala no considera la clasificación de los meteoros en función de su probabilidad de ocurrencia (Schott *et al.,* 2012).

Materiales y métodos

Área de estudio

El área de estudio corresponde al territorio del Estado de Guerrero, el cual se localiza en la región suroccidental de la república mexicana, junto con los estados costeros de Jalisco, Colima, Michoacán, Oaxaca y Chiapas (figura 1); los cuales en conjunto representan el 18% (2,066.05 km aprox.) de las costas del país. El Estado de Guerrero cuenta con una línea de costa aproximada de 1,950 km (INEGI, 1991).

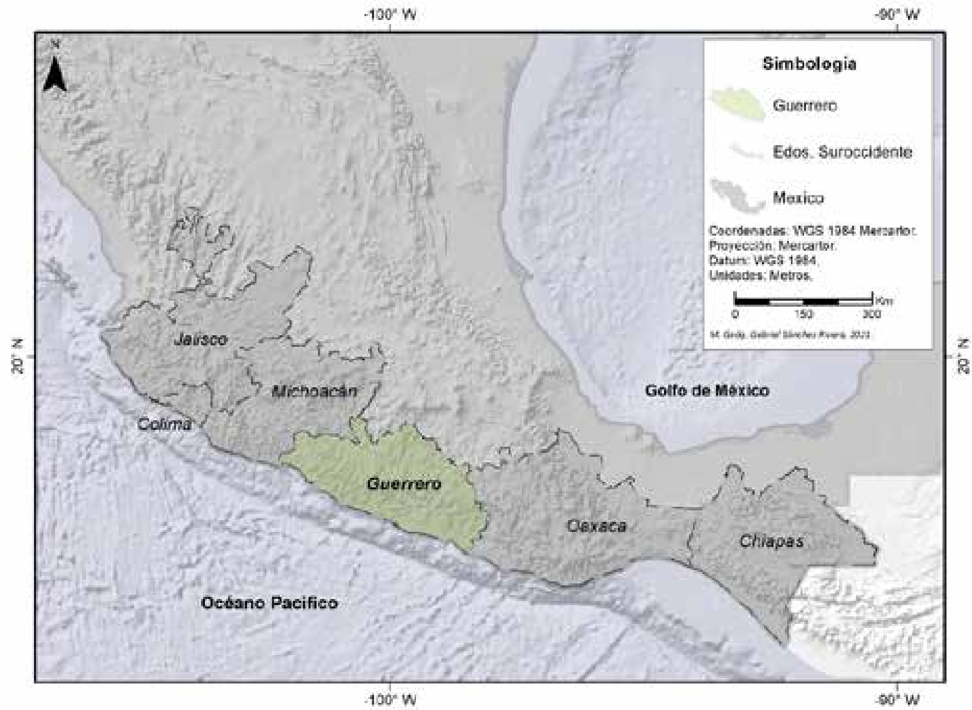


Figura 1: Región suroccidental de la república mexicana. Fuente: elaboración propia con datos de Amante y Eakins (2009), Flanders Marine Institute (2018) e (INEGI, 2019).

Datos

La información sobre las trayectorias y características físicas de los ciclones tropicales fueron adquiridas a través de los registros de la base de datos de la "mejor trayectoria" (IBTrACS, 2019), de la Administración Nacional Oceánica y Atmosférica —NOAA por sus siglas en inglés—. La información —de acceso público— es producto del reanálisis posterior a la temporada de ciclones, reportada en períodos de 6 h (Kenneth R. Knapp *et al.,* 2009).

Los registros del IBTrACS (2019), de acuerdo con K. R. Knapp *et al.* (2018), presentan variaciones espacio-temporales debido a que éstos son obtenidos de diversas fuentes entre las que se cuentan: observaciones superficiales, barcos, aeronaves e imágenes satelitales. De ahí que, para cada evento en particular, se tengan niveles de incertidumbre heterogéneos, asociados a diversas características como son: localización geográfica, intensidad, permanencia, año de formación, etc.

Para identificar los ciclones que impactaron el Estado de Guerrero se tomó como referencia el polígono que representa el territorio estatal del Marco Geoestadístico Nacional (INEGI, 2019).

Métodos

Los métodos y procedimientos para alcanzar los objetivos del estudio fueron los siguientes:

Adquisición y preprocesamiento de datos. Se homologaron todas las capas vectoriales a la proyección cartográfica UTM-GCS-WGS-1984 y se realizaron —según el caso— las conversiones de unidades al sistema métrico internacional.

Procesamiento de datos. Se construyó una base de datos correlacional a partir de la cual se efectuaron las consultas que permitieron identificar los ciclones que tocaron tierra en el país y en el Estado de Guerrero. Las operaciones se efectuaron mediante el lenguaje de programación SQL. Los procesos cartográficos y de análisis espacial se realizaron a través del Sistema de Información Geográfica —SIG— *ArcGis 10.3*.

Modelos, variables y parámetros de referencia. Para la identificar y caracterizar los ciclones tropicales como eventos extremos en función de la rareza de su ocurrencia —raros y muy raros—, se aplicó el modelo estadístico "excedente a un umbral relativo —*exceeding a relative threshold*—", tomado como umbrales de referencia los valores 0.1 y 99.9; 1.0 y 99.0; 10.0 y 90.0 percentiles (WMO, 2018; Sánchez-Rivera *et al.,* 2021). Las variables consideradas fueron la velocidad máxima de vientos sostenidos [km/h] y mínima presión atmosférica [mb].

Resultados

Caracterización de las temporadas 1951-2019

Los registros del IBTrACS reportan la formación de un total de 1,535 ciclones durante el período 1951-2019. De ellos, 104 (7%) tocaron tierra en los territorios de los estados costeros del suroccidente mexicano y, a su vez, 23 el Estado de Guerrero (cuadro 1), lo que posiciona a la entidad en el segundo puesto con la menor cantidad de impactos directos en su territorio, sólo por delante del Estado de Chiapas, el cual registra el impacto directo en su territorio de 10 eventos durante el mismo período.

De los 23 ciclones que ingresaron por el Estado de Guerrero, 48% (n = 11) alcanzaron la categoría —en escala S.S.— de huracán 1, y 13% (n = 3) la de huracán 4. No se reporta el impacto de ciclones en categorías 3 y 5.

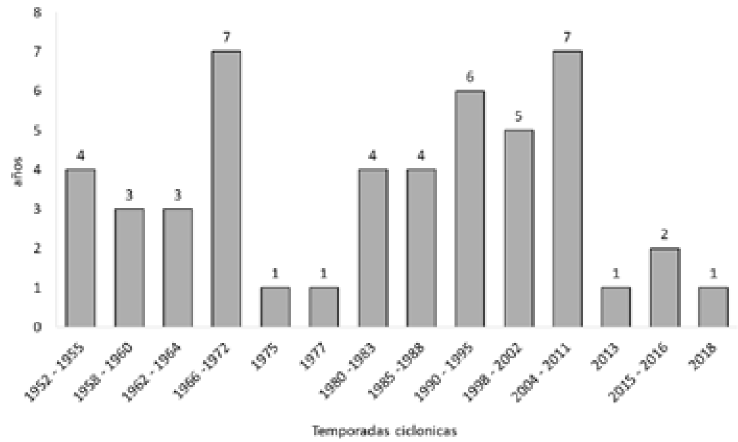
Cuadro 1: Ciclones que impactaron el Estado de Guerrero en el período 1951-2019.

Nombre	Año	Cat. / Dist. Total	Cat. / Dist. Tierra	% Trr / Total
Sin nombre	1951	DT / 939.78	TT / 94.0	10%
Wallie	1965	DT / 528.97	TT / 100.4	19%
Claudia	1973	DT / 1078.55	TT / 197.3	18%
Carlos	2003	DT / 833.51	TT / 132.7	16%
Trudy	2014	DT / 422.48	TT / 99.6	24%
Narda	2019	DT / 1925.67	TT / 18.7	1%
Sin nombre	1951	H1 / 1085.40	H1 / 335.2	31%
Sin nombre	1956	H1 / 894.47	H1 / 109.8	12%
Sin nombre	1957	H1 / 561.13	H1 / 15.8	3%
Iva	1961	H1 / 1124.15	H1 / 30.1	3%
Tara	1961	H1 / 862.64	H1 / 108.5	13%
Dolores	1974	H1 / 843.86	H1 / 130.8	16%
Norma	1974	H1 / 464.56	TT / 58.0	12%
Aletta	1978	H1 / 565.19	TT / 19.0	3%
Cosme	1989	H1 / 2306.67	H1 / 186.0	8%
Boris	1996	H1 / 1659.54	H1 / 86.1	5%
Max	2017	H1 / 423.71	H1 / 115.5	27%
Fifi:orlene	1974	H2 / 5759.72	DT / 86.0	1%
Odile	1984	H2 / 1349.47	H1 / 26.5	2%
Carlotta	2012	H2 / 1478.69	H1 / 282.0	19%
Madeline	1976	H4 / 1993.64	H3 / 25.3	1%
Ignacio	1979	H4 / 2437.71	DT / 42.4	2%
Pauline	1997	H4 / 1581.17	H1 / 461.0	29%

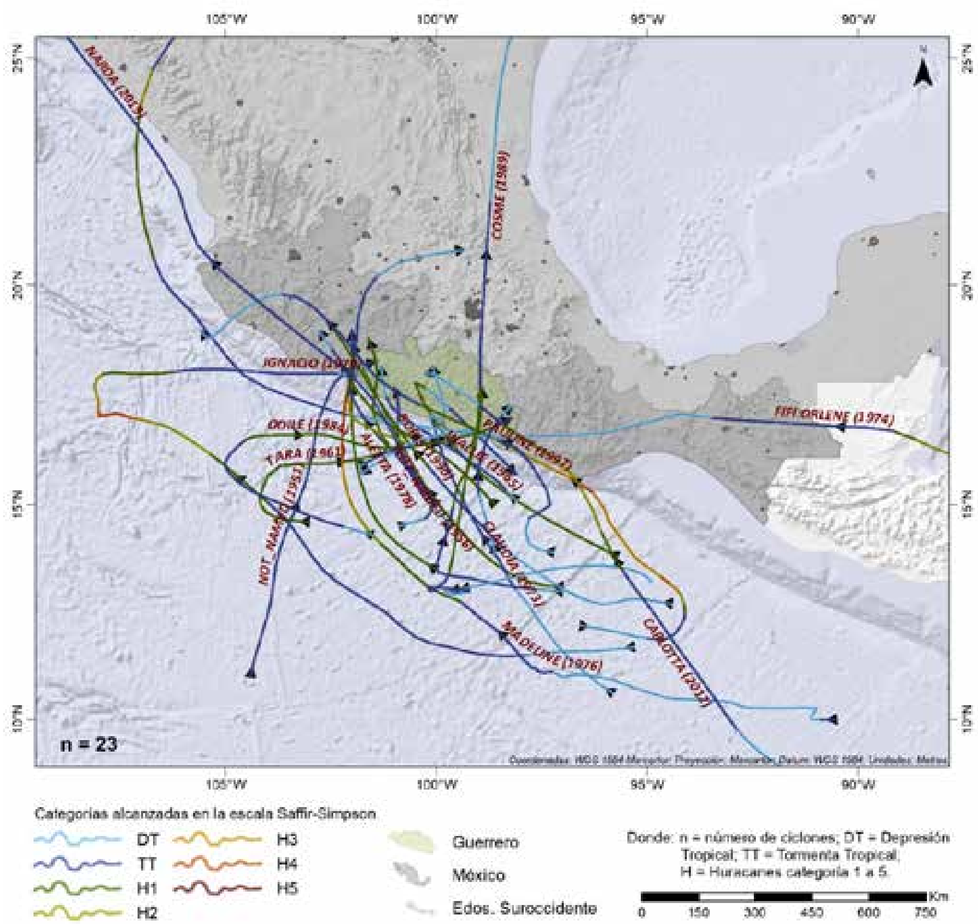
Donde: "Cat./Dist. Total" = Categoría S.S. y distancia total recorrida [Km]; "Cat./Dist. Tierra" = Categoría S.S. al impactar tierra y distancia recorrida en tierra [Km]; "% Trr / Total" = % de la distancia recorrida en tierra con respecto al total de la distancia recorrida por cada evento. Fuente: Elaboración propia con datos del IBTrACS (2019).

Durante el período estudiado (68 años) se identificó que en el 72% (n=49) de las temporadas de ciclones no hubo impactos directos en el territorio estatal, ocurriendo únicamente en el 28% (n= 19) de los casos. Sobresalen las temporadas de los años 1966-1972 y 1998-2002 con el máximo número de años consecutivos (7) sin impactos en tierra, seguido por las temporadas 1990-1995 con 6 años (figura 2).

Figura 2: Temporadas de ciclones sin impactos directos en tierra en el Estado de Guerrero.



Las trayectorias de los ciclones en categoría de huracán que han impactado el Estado de Guerrero, se presentan en la figura 3.



Fuente: Elaboración propia con datos del IBTrACS (2019).

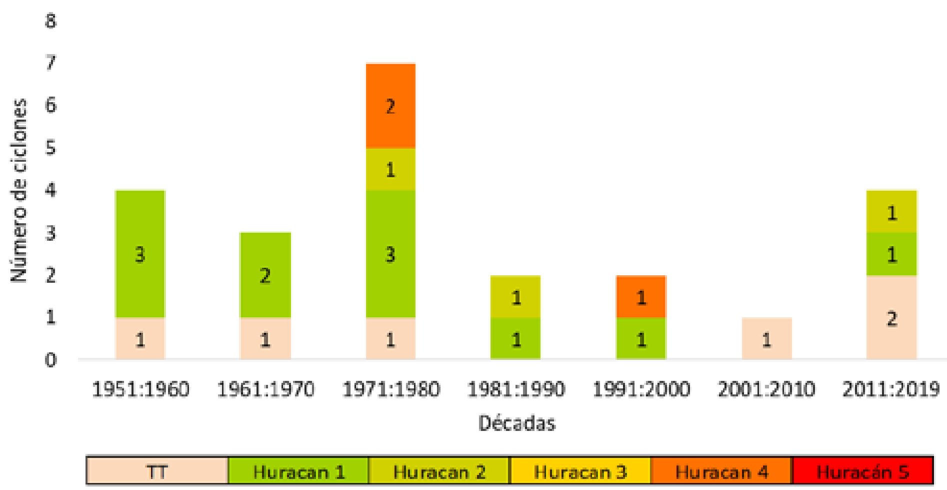
Figura 3: Trayectorias de los ciclones tropicales que impactaron las costas del Estado de Guerrero, agrupados por categorías en la escala Saffir-Simpson.

Para identificar los patrones de ocurrencia de los ciclones que han impactado la zona de estudio, se agruparon en función de décadas y categorías —escala S.S.—. Los resultados obtenidos muestran un comportamiento no homogéneo en la cantidad e intensidad de los eventos que han tocado tierra, no identificándose tendencia al alza tanto en cantidad como en intensidad. La década de los 70 del siglo XX, sobresale por presentar el mayor número de eventos registrados (7), seguida por las décadas de los 50 del mismo siglo y la segunda del siglo XXI, con un máximo de 4 eventos cada una. En contraste, es durante la primera década del presente siglo cuando se registra el mínimo impacto de meteoros en el estado, con sólo un evento en categoría máxima de tormenta tropical. Sobresale también el que no existe registro de impactos en territorio guerrerense de ciclones en categorías de huracán 3 y 5 (cuadro 2 y figura 4).

Cuadro 2: Número de ciclones por categoría y década en el período 1951-2019.

Décadas	En escala Saffir-Simpson (SS)						*Totales*
	TT	H1	H2	H3	H4	H5	
1951:1960	1	3					4
1961:1970	1	2					3
1971:1980	1	3	1		2		7
1981:1990		1	1				2
1991:2000		1			1		2
2001:2010	1						1
2011:2019	2	1	1				4
Totales	6	11	3	0	3	0	23

Figura 4: Número de ciclones agrupados por categoría —S.S.— y década en el período 1951-2019.



***Donde**: TT = Tormenta tropical. Fuente: Elaboración propia con datos del IBTrACS (2019).*

Ciclones categorizados como eventos extremos.

Los ciclones fueron caracterizados como eventos extremos mediante la aplicación del modelo excedente a un umbral relativo, tomando como base el total de meteoros reportados por el IBTrACS (2019) para el Pacífico nororiental (n = 1,535). Los resultados sitúan a los huracanes *Nancy* [H5, 1961] y *Patricia* [H5, 2015] como los de mayor intensidad, superando el umbral de 0.1 y 99.9 percentiles para las variables "mínima presión atmosférica" y "velocidad máxima de vientos sostenidos" respectivamente, lo que los posiciona en la categoría de "extremadamente raros" en función de su probabilidad de ocurrencia. El huracán *Nancy* no alcanzó tierras mexicanas, mientras que el huracán *Patricia* ingresó por el estado de Jalisco con valores extremos de "velocidad de vientos máximos sostenidos" de 342.6 km/h y "mínima presión atmosférica" de 872 mb. Siendo el huracán de mayor intensidad registrado en la zona en el período estudiado, incluso por encima del huracán *Wilma* [H5, 2005] formado en el Atlántico Norte y que impactara el Estado de Quintana Roo, en la península de Yucatán, y que alcanzara una "velocidad máxima de vientos sostenidos" del orden de los 296 km/h y "mínima presión atmosférica" de 882 mb.

En la categoría de eventos "muy raros" se identificaron 15 huracanes en categoría H5, que sobrepasaron los umbrales 1.0 y 99.0 percentiles y de los cuales ninguno impacto las costas de los estados del suroccidente mexicano: *Olive* [1952]; *Lola* [1957]; *Vera* [1959]; *Karen* [1962]; *Ruth* [1962]; *Kit* [1966]; *Irma* [1971]; *Tip* [1979]; *Gay* [1992]; *Joan* [1997]; *Linda* [1997]; *Paka* [1997]; *Dianmu* [2004]; *Rick* [2009]; *Vongfong* [2014].

En el caso del Estado de guerrero, dos (2) de los tres (3) ciclones que alcanzan tierra con categoría máxima de huracán 4, superaron los límites del umbral 90 percentiles para la variable "velocidad máxima de vientos sostenidos", cayendo en la categoría de eventos "raros". Los casos corresponden a los huracanes *Madelin* [H4, 1976] con "velocidad máximas de vientos sostenidos" de 231.5 km/h y "mínima presión atmosférica" de 941 mb e *Ignacio* [H4, 1979] con valores respectivos de 231.5 km/h y 938 mb (figura 5).

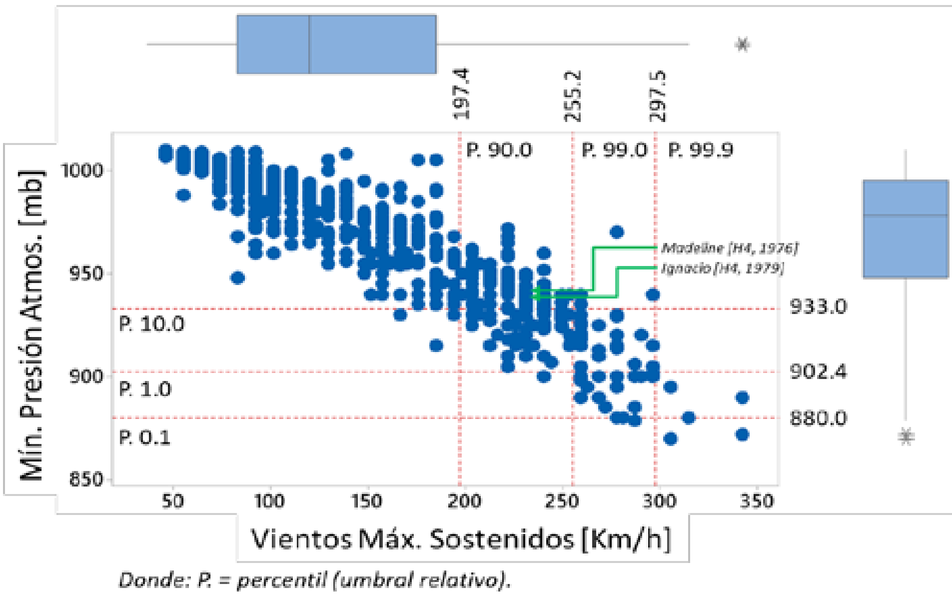


Figura 5: Diagrama de dispersión y valores de referencia del modelo excedente a un umbral relativo para los ciclones formados en el Pacífico nororiental.

Discusión y conclusiones

De acuerdo con los hallazgos obtenidos, no se identifica una tendencia al incremento en el número e intensidad —magnitud— de ciclones que han tocado territorio guerrerense, esto quizá se deba a como lo afirman Walsh (2004) y Walsh *et al.* (2016), que será hacia la década de los 50 del presente siglo, cuando se ponga de manifiesto un incremento en la intensidad máxima entre el 5% y 10% como consecuencia del calentamiento global derivado del cambio climático.

De la caracterización de los ciclones, como eventos extremos, destaca que de los ocho (8) ciclones en categorías H4 y H5 que han impactado las costas suroccidentales del país, dos (2) de ellos tocaron tierra firme en el Estado de Guerrero en categoría de eventos "raros" al superar los percentiles 10 y 90, no habiendo impactos de ciclones en categoría de "muy raros" o "extremadamente raros".

La mayoría de los ciclones en categoría de huracán que impactaron el estado alcanzaron categorías máxima de huracán 1.

De la revisión de la literatura científica en torno a concepto de eventos extremos, se constató que no existe un consenso para una definición única, dado que, como lo plantean Stephenson (2008) y la WMO (2018), el concepto es abordado desde diversas disciplinas como la meteorología, las ciencias biológicas y sociales, entre otras.

La caracterización de eventos en categoría de extremos —raros, muy raros y extremadamente raros— permite estimar las capacidades de resiliencia y vulnerabilidad de los sistemas socioecológicos y de los servicios ecosistémicos de los cuales depende la población de la región.

Los hallazgos del presente estudio pueden ayudar a coadyuvar con información necesaria para llevar a cabo estudios y proyectos que requieran la delimitación de zonas prioritarias de atención ante el impacto de fenómenos de alta intensidad y rara probabilidad de ocurrencia.

Finalmente, es necesario profundizar en el análisis y caracterización de eventos en categoría de extremos en función de la probabilidad de ocurrencia, tomando como referencia otras variables, como son la lluvia y los efectos sobre los sistemas socioecológicos y los servicios ecosistémicos, toda vez que en la literatura se reporta que no existe una relación directamente proporcional entre la categoría que alcanza un ciclón en la escala Saffir-Simpson y la ocurrencia de inundaciones y deslizamientos que ponen en riesgo a la población y sus medios de producción, dado que esto se encuentra vinculado a las condiciones de vulnerabilidad preexistentes.

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Microcrustaceans inhabiting tropical freshwater contaminated and non contaminated with arsenic: identification of regional suitable bioindicators.

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Research Article

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Abstract

We investigated microcustraceans inhabiting arsenic contaminated and non contaminated freshwater in order to identify those absent in arsenic contaminated water as suitable bioindicators of arsenic contamination in tropical freshwater in mining and metallurgical areas in northern Mexico. For doing so, we collected zooplankton, water and sediment samples, at five sampling points in two sampling campaigns, to determine water temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), alkalinity (Alk), salinity (Sal), and total arsenic concentration in water and sediments samples. We additionally determine arsenic mobility from sediments and its speciation. We also identified microcrustacean species and determined abundance, richness and Shannon Index. Results showed that the maximum arsenic concentration in freshwater was 53.23 mg/L, while the minimum arsenic concentration was < 0.01 mg/L. Arsenic concentration in sediments was between 10.37 mg/kg and 2472.84 mg/kg, with high arsenic mobility (up to 100%) where the arsenic leached was As(V). Nine species of microcrustaceans were found. *Simocephalus punctatus, Alona glabra, Eucyclops leptacanthus*, *Macrocyclops albidus* and *Pleuroxus (Picripleuroxus) quasidenticulatus*, inhabiting arsenic-free water, *Latonopsis australis, Eucyclops chihuahuensis*, *Acanthocyclops americanus, Pleuroxus (Picripleuroxus) quasidenticulatus*, *Macrocyclops albidus* and *Paracyclops chiltoni*, inhabiting moderately and highly contaminated water. *Simocephalus punctatus* (Orlova-Bienkowskaja, 1998) was absent in contaminated water bodies in study area, and therefore we proposed this microcustracean could serve as a bioindicator of water quality in waterbodies contaminated with arsenic in study area and northern Mexico, where arsenic contamination is common ground.

Introduction

Arsenic (As) is a chemical element present in the earth's crust and groundwater. In aqueous media, As speciation strongly depends on the redox condition of the aqueous system (De and Maiti, 2012). Under oxidizing conditions, inorganic As exists as arsenate (AsO_4^{3-}), with acidity constants (pKa) of 2.2, 6.9 and 11.5 for the species $H_3AsO_4^0$, $H_2AsO_4^-$, $HAsO_4^{2-}$, AsO_4^{3-}. On the other hand, in more reducing environments, inorganic As exists as arsenite (AsO_3^{3-}) with pKa values of 9.2, 12.1 and 13.4 where the uncharged ion $H_3AsO_3^0$ prevails at pH below 9.2 (Petrusevski et al., 2007; Ravenscroft et al., 2009; Samadzadeh Yazdi and Khodadadi Darban, 2010). The toxicity of As varies widely with its oxidation states. Arsenite is approximately 60 times more toxic than arsenate (Ventura-Lima et al., 2011). Arsenate is, in turn, 70 times more toxic than organic methylated species, such as monomethylarsonic acid (MMA) and dimethylarsine acid (DMA) (Akter et al., 2005). MMA and DMA are, in fact, considered only moderately toxic (Akter et al., 2005). Other As species, such as trimethylarsine oxide (TMAO) and tetramethylarsonium (TETRA) are also considered moderately toxic, while arsenobetaine (AsB), arsenocholine (AsC), and other arsenosugars (AsS) show no toxicity (Fattorini et al., 2006).

In aquatic environments, As can be incorporated into the food web, through different uptake routes: directly from solution across the entire body surface of the organisms, through specialized respiratory structures (eg, gills), or through the digestive epithelium with ingested food, water, sediments or suspended particles (Rahman et al., 2012).

Due to its toxicity, national and international authorities consider As within their regulations as a parameter for the protection of aquatic life. In Mexico, among the ecological criteria, the maximum permissible limit of As in water for the protection of aquatic life is set at 0.2 mg/L (DOF, 1989). For sediments, international regulations indicate a 17 mg/kg (CCME, 1999; EPA, 2002a) as a probable effect level (PEL) on freshwater aquatic organisms, while Mexican regulations need to be developed yet, for sediment quality purposes. For doing so, Mexico shall consider, as many other countries, biological parameters as they might provide better information than other descriptors for certain types of contamination (Cairns and Dickson, 1971; De la Lanza-Espino et al., 2011), such as phosphorus contamination in water, where chemical measurements may not accurately reflect a reduction in species diversity or how the growth and reproduction of other species may decline due to competitive exclusion (Holt and Miller, 2010). Furthermore, quantitative biological data is as easily accessible as physicochemical data.

In general, diverse feeding habits, very short life cycles, high reproductive rates and small sizes make microcrustaceans suitable as bioindicators. In this sense, the EPA (Environmental Protection Agency of the USA), developed a water quality standard using the cladocerans microcrustaceans *Daphnia pulex* and *Daphnia magna* as a bioindicators to determine acute toxicity in effluents and receiving waters to freshwater and marine organisms is the Method 2021.0 (EPA, 2002b), these species are highly sensitive to the presence of contaminants in water and therefore exhibits impacts on their level of reproduction, lifetime, and size of the individuals (Chen et al., 1999). In Mexico, the standard to evaluate acute toxicity in water analysis is the NMX-AA-087-SCFI-2010 (DOF, 2011), which, analogously to the Method 2021.0, uses *Daphnia magna* as a proxy. However, *Daphnia magna* is a species inhabiting cold and temperate climate being an exotic microcrustacean in Mexico, therefore it can not be considered representative for the monitoring of tropical aquatic ecosystems (Pérez-Legaspi et al., 2017). There is little research on tropical microcrustaceans, specifically cladocerans proposed to perform acute toxicity tests with some heavy metals (Do Hong et al., 2004; Freitas and Rocha, 2010; Hong and Li, 2007; Martínez-Jerónimo et al., 2008; Pérez-Legaspi et al., 2017; Rodgher et al., 2010), however, tropical microcrustaceans inhabiting contaminated freshwater with As have been poorly considered in these evaluations (Alvarado-Flores et al., 2019). Due to this, it is necessary to propose species of tropical microcrustaceans, widely distributed in Mexico that can be bioindicators of polluted environments, specifically with As.

A site that offers an excellent opportunity to study and understand As-related phenomena is Matehuala, San Luis Potosí, Mexico. In Matehuala, freshwater is contaminated with As due to current and historical metallurgical and mining activities (Martínez-Villegas et al., 2013; Pelallo-Martínez, 2006; Razo et al., 2004). Furthermore, As contamination has been reported to range from 4.78 mg/L to up to 158 mg/L (Martínez-Villegas et al., 2013), concentrations well above the recommended limits for the protection of aquatic life (0.2 mg/L) and the lethal concentration for zooplankton (3 mg/L). However, knowing this information raises the question of the existence of organisms in these conditions. This area gains importance and public interest since Matehuala contains recreation areas in which animal populations (including humans) are exposed to contact with contaminated water and sediment, and is a priority eco-region for the conservation and management of Mexico's aquatic biodiversity (Mercado-Salas and Suárez-Morales, 2012).

In this study, the species of microcrustaceans inhabiting freshwater were identified, as well as their ecological indicators. In addition, As concentrations in water and sediment were determined, as well as As speciation in the latter. A classification of the sampling points and species of microcrustaceans was made based on the concentration of As and alkalinity found in the water, in order to propose the bioindicator species. And, finally, to better understand any relationship between physicochemical parameters and ecological indicators, a correlation matrix was obtained and a principal components analysis was carried out.

Material And Methods

The study area corresponds to the municipality of Matehuala, San Luis Potosi, Mexico, formed by a set of closed basins, where rainfall and groundwater are the water sources. Soils are Xerosol type, with gypsum in the deep horizon and soil cemented with carbonate at a shallow depth (Gómez-Hernández et al., 2020).

Water and microcrustaceans samples were collected through two sampling campaigns (S1 and S2) at five different sites: Club de Tiro, Abrevadero, Laguna, Presa, and Canal. While the first three sites correspond to a complex with As contaminated water (Martínez-Villegas et al., 2013; Razo et al., 2004), the other two sampling points are As-free. Additionally, sediment samples were collected in an additional sampling campaign at Club de Tiro, Laguna y Presa. All samping sites were located within the urban area of Matehuala city (Fig. 1).

Location of the sampling points: 1) Club de Tiro, 2) Abrevadero, 3) Laguna, 4) Presa, and 5) Canal.

Ten water samples were collected in 60 mL polypropylene containers previously washed with 2% Extran® and 10% HNO_3 acid. Water samples were filtered through Whatman filter paper #40 (125 mm), acidified to pH < 2 with concentrated HNO_3, closed and stored at 4°C until analysis to determine As. For quality control and assurance, one laboratory blank, one field blank and one duplicate were collected at each sampling campaign.

Water temperature, pH, electrical conductivity, dissolved oxygen, and salinity were measured onsite using a multiparameter probe (HANNA Instruments Model 9829 Handheld MultiparameterWater Quality Meter). Additionally, alkalinity was determined by titration using an Automatic Titration Kit of the HACH brand model AL-DT.

As concentrations in water samples were determined by Inductive Coupling Plasma Optical Emission Spectroscopy (ICP-OES), using a Varian 730 ES spectrometer (EPA, 1994). Calibration with reference samples and blanks as well as replicate analyses for quality control were carried out to ensure the reliability of the analytical data. The calibration curve was in the range of 0.05-20 mg/L, while the detection limit was 0.001 mg/L.

Additionally, 100 L of freshwater were filtered through a 50 µm mesh to capture zooplankton; once in a collecting glass, zooplankton organisms were fixed with concentrated ethyl alcohol (90%) until analysis. All zooplancton specimens were sorted and taxonomically examined using specialized literature (Elias-Gutierrez et al., 2008; Korovchinsky, 1992). Adult abundance (organisms/L) was estimated by total counting on an Eclipse E-400 compound microscope for each species. The diversity was calculated using the Shannon Index (Shannon, 1948): $H' = -\sum pi \ln(pi)$, where pi is the relative abundance of the ith species.

Sediment samples were collected at Club de Tiro, Laguna, and Presa in aluminum foil bags using a shovel, previous cleanup of rocks and vegetation. All sediment samples were kept at 4°C until As analysis. In the laboratory, the sediment samples were dried in an oven at 60°C for 24 h. Then, 0.25 g of homogenized samples were predigested in 4 ml of 65% HNO_3 overnight at room temperature in triplicates. Subsequently, the samples were gently shaken and digested in the microwave using the BASIC OPEN program with a ramp of 5 min to 55°C and 10 min of digestion. Finally, each digest was diluted to 50 ml in 1% HNO_3 and centrifuged for 5 min at 2500 rpm. Total As concentrations in the supernatants were determined by inductively coupled plasma mass spectrometry (ICP-MS Agilent 7700 Series) (Hossain et al., 2012; Mestrot et al., 2011). Additionally, As speciation was determined in dry sediment samples, crushed in an Agate mortar. For doing so, 0.25 g of homogenized samples were predigested in 4.8 ml of 1% HNO_3, in order to recover the most possible amount of As in the sample. Subsequently, microwave digestion was carried out using the BASIC OPEN program with a ramp of 5 min to 55°C and maintaining this temperature for 10 min. After, the supernatants were centrifuged for 5 minutes at 2500 rpm and As speciation in sediments was determined using an ICP-MS Agilent 7700 Series coupled to an high performance liquid chromatography (HPLC Agilent 1260 Infinity) with an anion exchange PRP X-100 HPLC column (Hossain et al., 2012; Mestrot et al., 2011; Viacava et al., 2020) to determine inorganic As (As(III) and As(V)) and arsenicals (TMAsO, DMAs(V) or MMAs(V)).

The correlation between physicochemical (water temperature, electrical conductivity, dissolved oxygen, pH, salinity, alkalinity, As) and ecological (richness, Shannon index, and abundance) variables was determined in order to establish any relationship among the hydrogeochemistry and the attributes of the organisms. PCA was carried out using OriginPro, Version 2016 (OriginLab Corporation, Northampton, MA, USA).

Results

Table 1 shows water temperature, pH, electrical conductivity, dissolved oxygen, alkalinity and salinity. Water temperature ranged from 16.9 to 23.7°C, pH was between 6.7 and 8.3, electrical conductivity ranged from 2364 to 3282 µs/cm, dissolved oxygen ranged from 0.6 to 3.7 mg/L, alkalinity was between 11.2 and 296 $mgCaCO_3/L$, and salinity ranged between 0.7 and 1.7‰. Water pH values are the results of the buffer capacity of limestone (Razo et al., 2004), while electrical conductivity values are the result of calcite and gypsum dissolution in the aquifer (Gómez-Hernández et al., 2020). Small variations on water temperature and dissolved oxygen were observed, however they are typical of groundwater at tropical altitudes (Caspers et al., 1981), suggesting typical environmental conditions. A high transparency, as well as a low amount of algae or aquatic vegetation and low biomass were observed in the studied water bodies, which allowed their classification as "oligotrophic systems" according to Roldán and Ramírez, (2008).

Table 1
Water temperature (T), pH, electric conductivity (EC), dissolved oxygen (DO), alkalinity (Alk), and salinity (Sal) measured *in situ* at two sampling campaigns (S1 and S2) at the different sampling sites. S.D.= Standard deviation.

Site	Sampling	T (°C)	pH	EC (µs/cm)	DO (mg/L)	Alk ($mgCaCO_3/L$)	Sal (‰)
Club de Tiro	S1	22.5	6.7	2762.0	1.3	219.0	1.4
	S2	21.5	6.7	3209.0	0.6	296.0	1.7
	Mean	22.0	6.7	2985.5	0.9	257.5	1.5
	S.D.	0.7	0.0	316.0	0.5	54.4	0.2
Abrevadero	S1	21.1	7.0	2364.0	3.4	121.0	0.7
	S2	20.5	7.5	2376.0	0.7	193.0	1.3
	Mean	20.8	7.2	2370.0	2.0	157.0	1.0
	S.D.	0.4	0.3	8.4	1.9	50.9	0.4
Laguna	S1	20.9	7.5	2423.0	3.6	90.0	1.2
	S2	20.4	8.3	2591.0	0.9	11.2	1.3
	Mean	20.6	7.9	2507.0	2.3	50.6	1.2
	S.D.	0.3	0.6	118.8	1.8	55.7	0.1
Presa	S1	23.7	7.3	2892.0	2.6	103.0	1.6
	S2	18.7	7.7	3282.0	0.9	142.0	1.7
	Mean	21.2	7.5	3087.0	1.7	122.5	1.6
	S.D.	3.5	0.3	275.7	1.2	27.6	0.1
Canal	S1	18.8	7.4	2528.0	3.7	127.0	1.2
	S2	16.9	7.8	2888.0	1.3	169.5	1.5
	Mean	17.8	7.6	2708.0	2.5	148.2	1.3
	S.D.	1.3	0.3	254.5	1.7	30.1	0.2

Figure 2 shows As concentrations in water samples, which ranged between < 0.01 mg/L and 53.23 mg/L. At Club de Tiro, As concentrations were 38.98 mg/L and 53.23 mg/L, during S1 and S2, respectively. In Abrevadero, As concentrations were 1.62 mg/L and 5.91 mg/L, during S1 and S2, respectively. In Laguna, As concentrations were 1.9 mg/L and 5.3 mg/L, during S1 and S2, respectively. Canal and Presa showed the lowest concentrations of As in water with values between < 0.01 mg/L and 0.2 mg/L, respectively. More importantly, 6 out of the 10 water samples were above the maximum permissible levels of As in water for irrigation, recreation and protection of aquatic life (CCME, 2001; DOF, 1989). All contaminated water samples were collected from Club de Tiro, Abrevadero and Laguna. Furthermore, some of these samples were also above the As lethal concentration reported for zooplankton (3 mg/L) (Chen et al., 1999), highlighting a likely risk for microcrustacean life in the impacted water bodies.

As concentrations in water simples, in squares the data of sampling 1 and in triangles the data of sampling 2, additionally the maximum permissible As concentration in natural waters (0.2 mg/L) in Mexico (DOF, 1989) as well as the As lethal concentration for zooplankton (3 mg/L) are presented in dotted lines (Chen et al., 1999).

Figure 3 shows total As concentration in sediment samples for contaminated and non-contaminated sampling sites. Total As concentrations in sediment were 2472.84 ± 611.48 mg/kg at Club de Tiro, 553.48 ± 9.11 mg/kg at Laguna, and 10.37 ± 5.39 mg/kg at Presa, which largely exceed the international guideline values for As in sediments for quality purposes (5.9 mg/kg) (CCME, 1999) as well as the probable effect level of As for freshwater aquatic organisms (17 mg/kg) (CCME, 1999; EPA, 2002a). So far, up to date, no regulations are available in Mexico for sediment quality. Additionally, a high mobility of As, from the sediments, was found in this study, which accounted for 47.20% of the total As at Club de Tiro, 52.19% of the total As at Laguna, and 100% at Presa as determined by the recovery of As using 1% HNO_3. Considering that As recoveries in acid digestions using concentrated acids (> 65%) are between 85 and 99.9% (Davidowski and Sarojam, 2012), As mobility at Club de Tiro and Laguna using mild acid might have been limited by the experimental conditions (solid to solution ratio and reaction time), highlighting the possibility of being higher than the values obtained in this study and the risk of the samples. We also found that the mobile As was actually As(V). No methylated As (III) species were found in sediments. This, likely due to the minerals that were suggested to control the mobility of As in the study area, which accounted for calcium arsenates (Martínez-Villegas et al., 2013). Similarly, in this study, the oxidation state of As was + 5.

Total As concentration in sediment samples, recovery percentages of As in sediment digestions using 1% HNO_3 and the maximum permissible concentration of As for the protection of healthy aquatic systems (17 mg/kg) is presented in red dotted line (CCME, 1999).

Table 2 shows the ecological indicators for each sampling site and time. Abundance ranged from 0 to 25.17 org/L, richness was between 0 and 4, and Shannon index ranged from 0 to 1.24, showing that the site with the greatest species richness was Laguna. For Canal, we found absence of zooplankton likely due to the water flow that may complicate the survival of the organism in the stream of the channel. Typically, Shannon index values are between 2 and 3, values less than 2 are considered low in diversity and greater than 3 are high in species diversity (Margalef, 1972). Therefore, the sampling sites studied here exhibited low diversity, with Club de Tiro exhibiting the lowest diversity, with Shannon indexes of zero at two sampling campaigns.

Table 2
Ecological indicators obtained from microcrustaceans samples.

Site [As mg/L]	**Sampling**	**Abundance (org/L)**	**Richness**	**Shannon Index**
Club de Tiro 38.98–53.23	S1	0.32	1	0
	S2	25.17	1	0
Abrevadero 1.62–5.91	S1	1.45	3	0.49
	S2	0.25	1	0
Laguna 1.9–5.3	S1	3.91	4	0.67
	S2	2.49	4	0.89
Presa 0.01–0.2	S1	11.54	4	1.24
	S2	7.88	2	1.12
Canal < 0.01	S1	0.21	2	0.19
	S2	0.00	0	ND

Table 3 shows the cladoceran (Crustacea; Branchiopoda: Ctenopoda, Anomopoda) and copepod (Crustacea: Copepoda, Cyclopoida) species inhabiting the surveyed systems in both sampling periods.

In non-contaminated sampling points (0.0-0.2 mg/L), 5 species of microcrustacean were found (*Simocephalus punctatus, Alona glabra, Eucyclops leptacanthus*, *Macrocyclops albidus* and *Pleuroxus (Picripleuroxus) quasidenticulatus*). In the moderately contaminated sampling points (1.61–5.91 mg/L), 4 species were found (*Latonopsis australis, Pleuroxus (Picripleuroxus) quasidenticulatus, Eucyclops chihuahuensis*, *Acanthocyclops americanus Paracyclops chiltoni*), while in the most contaminated sampling point (up to 53.23 mg/L) only one species was found (*Pacacyclops chiltoni*).

Additionally, two species were found to cohabite As free and contaminated water, namely *Pleuroxus (Picripleuroxus) quasidenticulatus* and *Macrocyclops albidus.* One species was found cohabiting As moderately contaminated and highly contaminated water, while 4 species were found only in non contaminated water. Large species like *Simocephalus punctatus* (Cladocera: Anomopoda) were the most abundant in absence of As (6.06 org/L), whereas smaller microcrustacean, like the copepod *Paracyclops chiltoni* (Copepoda: Cyclopoida), inhabiting the most As contaminated water, showed an abundance up to 25.17 org/L, which was, in turn, the highest abundances found among all sampling points.

Table 3
Microcrustacean species inhabiting non-contaminated and contaminated freshwater in Matehuala, San Luis Potosi, Mexico.

Level of As (mg/L)	**Sampling point**	**Specie**	**Distribution***	**Highlights**
0.00–0.02	Presa	*Simocephalus punctatus* (Orlova-Bienkowskaja, 1998)	Canada, U.S.A., and North of Mexico (Nearctic species).	Intermediate alkalinity ranged from 100–170 $mgCaCO_3/L$; zooplankton of longer body size with abundances ranged from 10–100 org/L.
	Presa	*Alona glabra* (Sars, 1901)	South America and some localities in Central Mexico.	
	Presa	*Eucyclops leptacanthus* (Kiefer, 1956)	South and Central America, and North of Mexico.	
	Presa and Canal	*Pleuroxus (Picripleuroxus) quasidenticulatus* (Smirnov, 1996)$^{-}$	Cosmopolitan, recorded in Europe, Asia, North, Central and South America.	
	Canal	*Macrocyclops albidus albidus* (Jurine, 1820)$^{+}$	Cosmopolitan, in North, Central and Southeastern of Mexico.	
1.61–5.91	Laguna	*Latonopsis australis* (Sars, 1888)	Presumably cosmopolitan, probably a species complex.	Low alkalinity from 11 to 190 $mgCaCO_3/L$; zooplankton of medium body size, with abundance ranged from 0 to < 10 org/L.
	Laguna	*Macrocyclops albidus albidus* (Jurine, 1820)$^{+}$	Cosmopolitan, in North, Central and Southeastern of Mexico.	
	Laguna	*Acanthocyclops americanus* (Marsh, 1893)	Considered as a cosmopolitan species.	
	Abrevadero and Laguna	*Pleuroxus (Picripleuroxus) quasidenticulatus* (Smirnov, 1996)$^{-}$	Cosmopolitan, recorded in Europe, Asia, North, Central and South America.	

* Distribution and body size data found in the Barcode of Life Data System v4 database (BOLD, 2021).

−,+ Species found in two sites and different concentrations of As.

Level of As (mg/L)	Sampling point	Specie	Distribution*	Highlights
	Abrevadero and Laguna	*Eucyclops chihuahuensis* (Suárez-Morales and Walsh, 2009)	Possibly endemic to a few localities in the North of Mexico.	
5.91–53.23	Abrevadero and Club de Tiro	*Paracyclops chiltoni* (Thomson, 1883)	Cosmopolitan, widely distributed in North and South America.	High alkalinity from 220 to 300 mg$CaCO_3$/L; zooplankton of short body size, with abundance ranged from 1 to 60 org/L.
* Distribution and body size data found in the Barcode of Life Data System v4 database (BOLD, 2021).				
–,+ Species found in two sites and different concentrations of As.				

Figure 4 shows the PCA. PC1 (38.31%) combined electrical conductivity, salinity, alkalinity, As and abundance, while the PC2 (28.39%) combined pH, richness and Shannon index. These two main components explained 66.70% of the total variability of the data. Table 3 shows the parameter coefficients to each principal component.

Figure 4 and Table 4 suggest that PC1 was a factor that combined abiotic and biotic aspects related to mineral solubility and abundance of zooplankton, which was supported by a positive correlation between the level of electrical conductivity and salinity, as well as salinity and abundance and alkalinity and As (Table 5). Salinity is considered one of the most important environmental factors that shapes the biodiversity and abundance of zooplankton (Ojaveer et al., 2010; Perumal et al., 2009; Yuan et al., 2020). It has been reported that the groups of zooplankton most affected by salinity are rotifers and cladocerans, showing a decrease in their abundances and diversities (Ojaveer et al., 2010; Yuan et al., 2020). On the other hand, copepods show little effect on abundance with increasing salinity, and even positive correlations have been reported between salinity and abundance of copepods in freshwater (Perumal et al., 2009), as in the case of this work. In this study, electrical conductivity showed a relationship with salinity as a result of calcite and gypsum dissolution. In the study area, water evaporation and mineral dissolution explain the positive correlation between the concentration of As and alkalinity as well (Table 5).

PC2 was a biotic factor related to pH, which was supported by a positive correlation between pH and richness. It has been reported that, although zooplankton organisms show a high degree of tolerance to changes in pH, negative effects in abundance and richness have been related to moving away from neutrality (Echaniz et al., 2012).

PCA biplot showing PC1 and PC2 as well as the contribution variables of each component. The physicochemical and ecological variables are presented in blue and the sampling sites in red.

Table 4
Extracted eigenvectors.

	Coefficients of PC1	Coefficients of PC2
Abundance	**0.36559**	0.26023
Shannon	0.21621	**0.36870**
Richness	-0.07763	**0.46492**
T	0.05217	-0.21034
pH	-0.20972	**0.47342**
EC	**0.44508**	0.17796
DO	-0.34911	-0.13026
Alk	**0.38742**	-0.31489
Sal	**0.41569**	0.21547
As	**0.35213**	-0.34292

Table 5
Pearson's correlation matrix between ecological and physicochemical parameters, showing values > 0.5 in red and <-0.5 in blue.

	Abundance								
Shannon	0.5326	**Shannon**							
Richness	0.2623	0.5277	**Richness**						
T	-0.1504	0.0847	0.1367	**T**					
pH	-0.0706	0.1243	0.5687	-0.5386	**pH**				
EC	0.8075	0.4491	0.0299	-0.0823	-0.1309	**EC**			
DO	-0.4005	-0.2664	-0.0354	0.1027	-0.1218	-0.5328	**DO**		
Alk	0.3017	0.1005	-0.6239	0.0647	-0.7276	0.4316	-0.4161	**Alk**	
Sal	0.5963	0.5067	0.0745	-0.0208	0.0398	0.8536	-0.6225	0.3780	**Sal**
As	0.1966	-0.1773	-0.3765	0.3923	-0.6856	0.3941	-0.4567	0.7549	0.3429

In this survey, the cosmopolitan *P. chiltoni* probed to be a copepod highly tolerant to extremely high concentrations of As. The presence of *P. chiltoni* has been recorded in systems with different trophic states and in the littoral or planktonic habitats in worldwide freshwater systems (Lansac-Tôha et al., 2002). In this study, *P. chiltoni* was the only species inhabiting a system with more than 50 mg/L of As with Shannon Indexes of zero. That is, *P. chiltoni* seems to be resistant to severe stress and thrive in extreme conditions, providing additional evidence as an extremophile crustacean as previously reported in Mendoza-Chávez et al., (2021).

Based on the results from this study, 4 species inhabiting the Canal and Presa (*Simocephalus punctatus, Alona glabra, Eucyclops leptacanthus* and *Macrocyclops albidus*) may exhibit potential as likely bioindicators vulnerable to As contamination and alkalinity. Species of the genus *Simocephalus*, *S. mixtus* and *S. serrulatus* have been reported

(Martínez-Jerónimo et al., 2008; Nogueira et al., 2008) to show great sensitivity in toxicological tests and bioassays, even with better sensitivities than the commonly used tested *Daphnia*. Therefore, we suggest *Simocephalus puntactus* as a likely bioindicador for As contamination in freshwater, genus that meet the characteristics of bioindicators, such as short life cycles, diverse feeding habits, small sizes and high reproductive rates (Chakri et al., 2014; Murugan and Sivaramakrishnann, 1973; Sharma and Pant, 1982). Especially because, unlike *Daphnia*, the species recommended for toxicity tests in the country's regulations, this species is distributed in Mexico (Elias-Gutierrez et al., 2008; Young et al., 2012).

On the other hand, species inhabiting water contaminated with As, such as *Latonopsis australis, Pleuroxus (Picripleuroxus) quasidenticulatus, Eucyclops chihuahuensis*, *Acanthocyclops americanus* and *Paracyclops chiltoni*, could be studied in the future to better understand As methylation in freshwater organisms, as well as their possible adaptations to survive.

Conclusions

As contamination in freshwater and sediment from Matehuala account for up to 53.23 mg/L and 2472.84 mg/kg, respectively. Such values are orders of magnitude higher than the Mexican guidelines for the protection of aquatic life (0.2 mg/L and 17 mg/kg). Yet, microcrustaceans, as the extremophile *P. chiltoni*, were found in this contaminated environment, while *Simocephalus punctatus, Alona glabra, Eucyclops leptacanthus* and *Macrocyclops albidus* inhabiting As free freshwater in the study area could served as bioindicators of As contamination conditions, especifically, the species *S. punctatus*, whose genus has shown good results in ecotoxicology. Microcrustacean species reported in this study offer opportunities to better understand the incorporation of As in the trophic chain and likely morphologic/genotypic As adaptations.

Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Yadira J. Mendoza-Chavez: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. Jose L. Uc-Castillo: Formal analysis & Investigation. Adrian Cervantes-Martínez: Methodology, Investigation, Formal analysis, Writing - review & editing. Martha A. Gutierrez-Aguirre: Methodology, Formal analysis, Writing - review & editing. Nadia Martínez-Villegas: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Data Availability

All data generated or analysed during this study are included in this published article.

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Figures

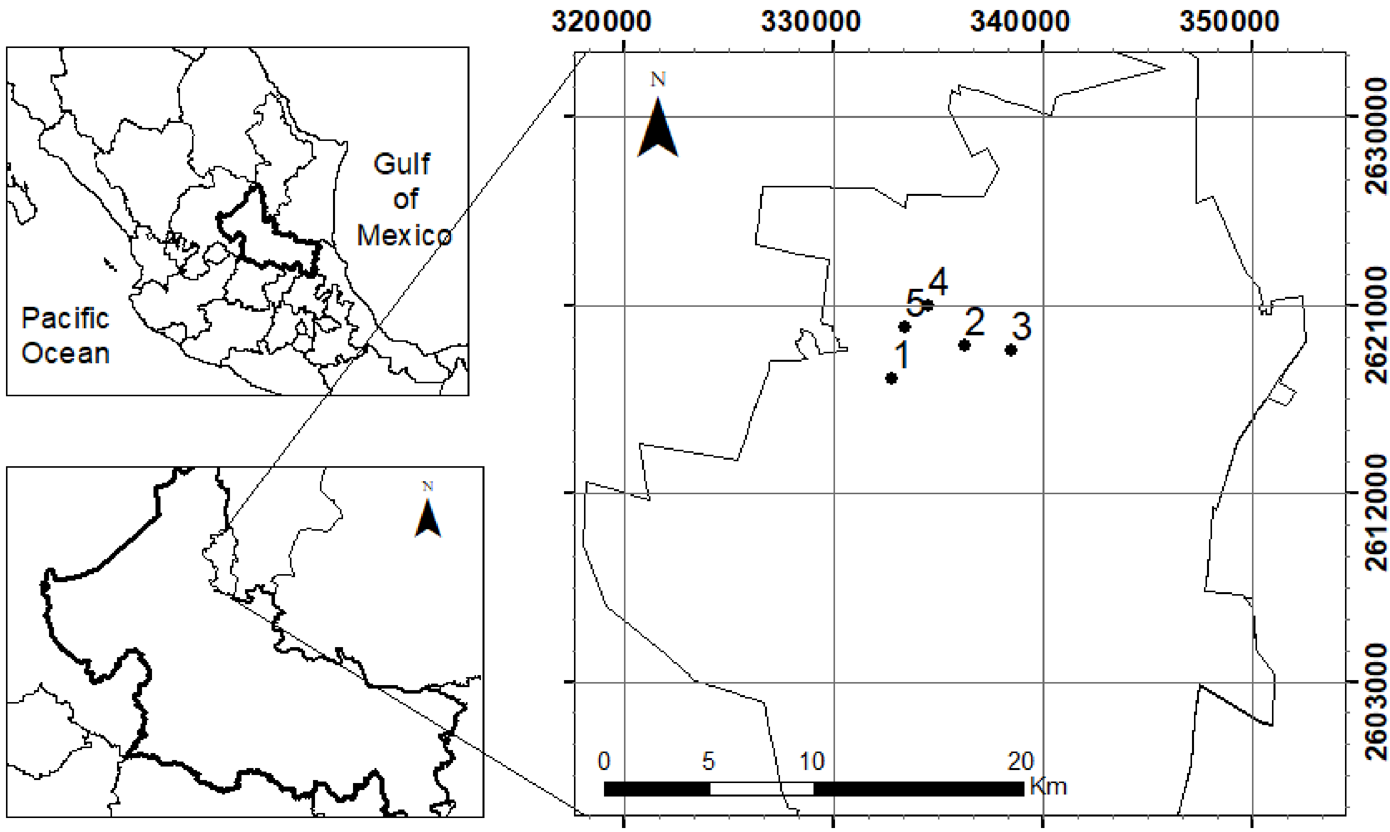

Figure 1

Location of the sampling points: 1) Club de Tiro, 2) Abrevadero, 3) Laguna, 4) Presa, and 5) Canal.

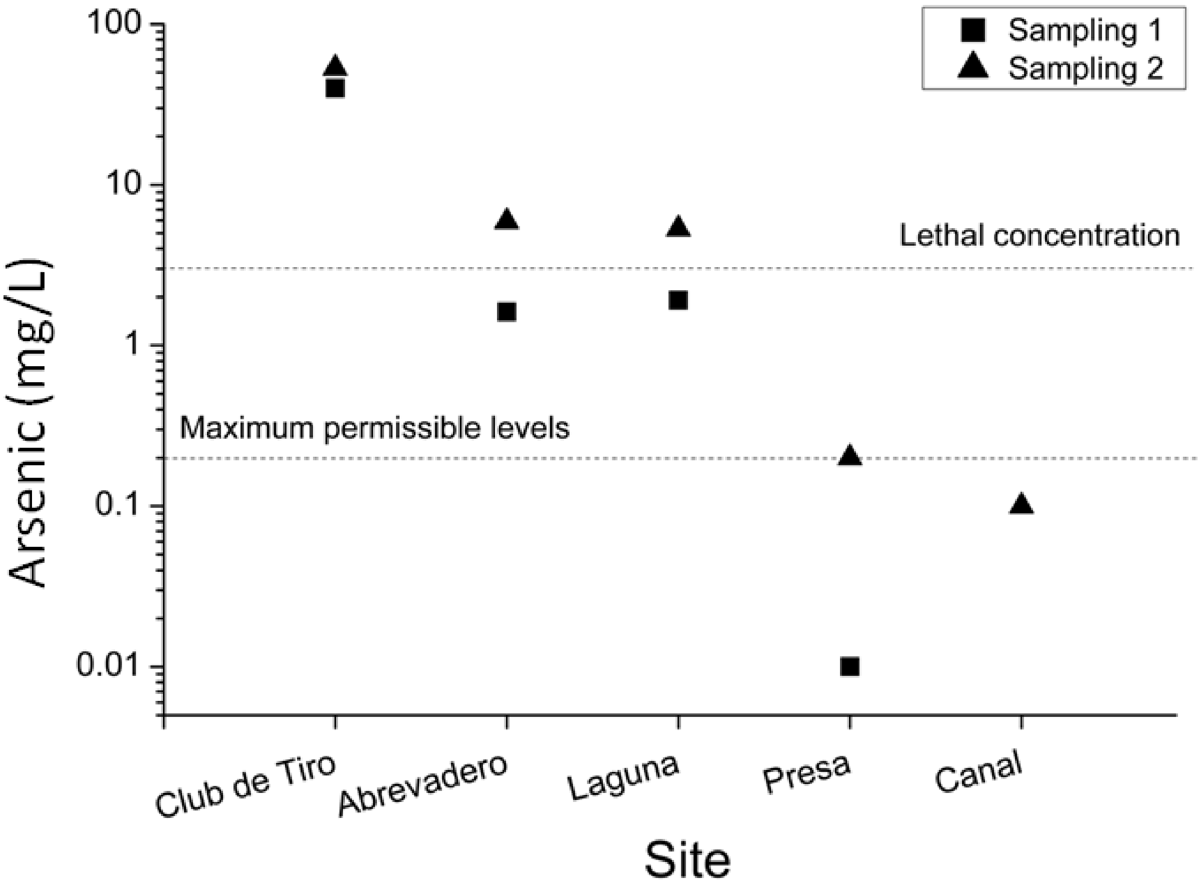

Figure 2

As concentrations in water simples, in squares the data of sampling 1 and in triangles the data of sampling 2, additionally the maximum permissible As concentration in natural waters (0.2 mg/L) in Mexico (DOF, 1989) as well as the As lethal concentration for zooplankton (3 mg/L) are presented in dotted lines (Chen et al., 1999).

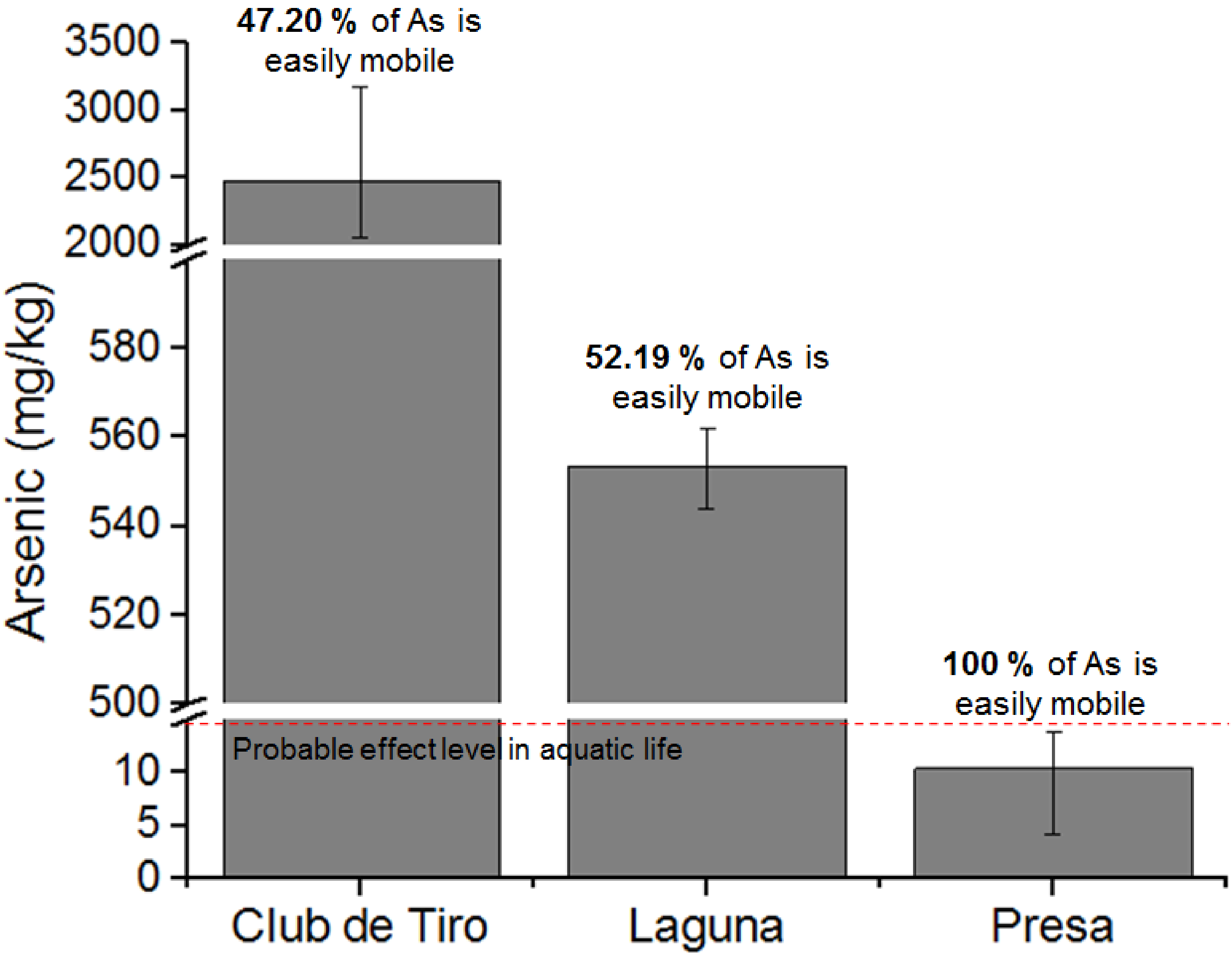

Figure 3

Total As concentration in sediment samples, recovery percentages of As in sediment digestions using 1% HNO_3 and the maximum permissible concentration of As for the protection of healthy aquatic systems (17 mg/kg) is presented in red dotted line (CCME, 1999).

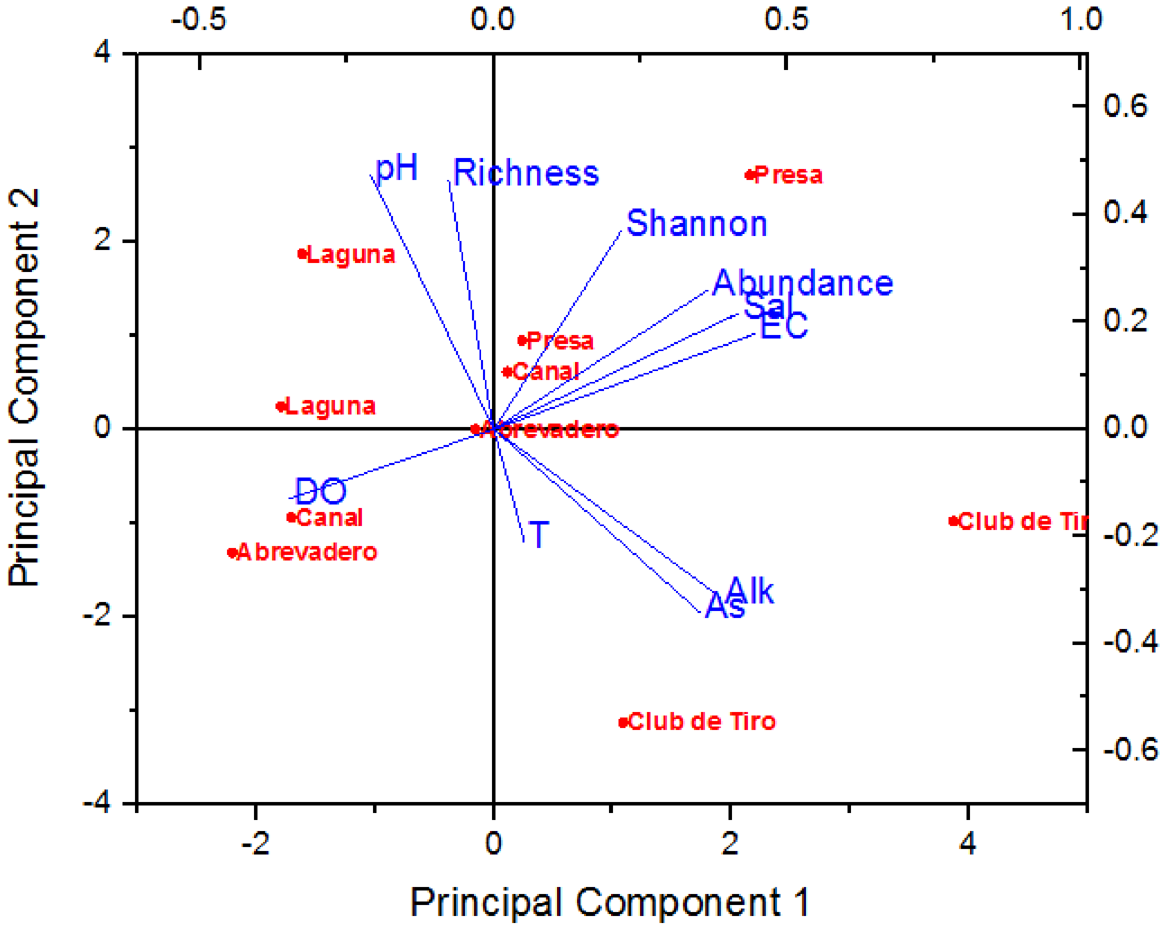

Figure 4

PCA biplot showing PC1 and PC2 as well as the contribution variables of each component. The physicochemical and ecological variables are presented in blue and the sampling sites in red.