ReGeo ISSN: 2177-3246

IMPACTS OF EMERGING CONTAMINANTS ON HUMAN HEALTH AND WATER SECURITY: AN INTERDISCIPLINARY ANALYSIS WITH A FOCUS ON THE PCJ BASINS

IMPACTOS DE CONTAMINANTES EMERGENTES NA SAÚDE HUMANA E SEGURANÇA HÍDRICA: UMA ANÁLISE INTERDISCIPLINAR COM FOCO NAS BACIAS PCJ

IMPACTOS DE LOS CONTAMINANTES EMERGENTES EN LA SALUD HUMANA Y LA SEGURIDAD HÍDRICA: UN ANÁLISIS INTERDISCIPLINARIO CON ENFOQUE EN LAS CUENCAS PCJ

doi 10.56238/revgeov17n3-014

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ABSTRACT

The Piracicaba, Capivari, and Jundiaí (PCJ) river basins face critical water security challenges due to intense urbanization and agro-industrial activities, which introduce a complex load of pollutants into water bodies. The central research problem lies in the need to understand how emerging contaminants (physical-chemical and microbiological) impact human health and ecosystem integrity, especially in a scenario of climate and social vulnerability. The objective of this study is to identify and map these contaminants and their effects on public health, evaluating the effectiveness of current detection methods. The methodology adopted a mixed approach, based on a systematic review of the literature according to the PRISMA protocol and the PICO strategy. Thirty-seven articles selected from high-impact databases (Scopus, PubMed, Web of Science) were analyzed, filtered from an initial universe of 3,135 publications. The results reveal a spatial dichotomy: industrial areas have a high incidence of heavy metals and persistent organic compounds, while regions with poor sanitation suffer from microbiological contamination. A direct correlation was identified between water quality and an increase in infectious diseases, cancer risks, and antimicrobial resistance. The study concludes that sustainable management in the PCJ Basins requires the implementation of advanced monitoring and integrated public policies

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that prioritize the protection of vulnerable populations and water security.

Keywords: PCJ Basins. Emerging Contaminants. Human Health. Water Quality. Water Resource Management.

RESUMO

As Bacias dos rios Piracicaba, Capivari e Jundiaí (PCJ) enfrentam desafios críticos de segurança hídrica devido à intensa urbanização e atividades agroindustriais, que introduzem uma complexa carga de poluentes nos corpos d'água. O problema de pesquisa central reside na necessidade de compreender como os contaminantes emergentes (físico-químicos e microbiológicos) impactam a saúde humana e a integridade ecossistêmica, especialmente em um cenário de vulnerabilidade climática e social. O objetivo deste estudo é identificar e mapear esses contaminantes e seus efeitos na saúde pública, avaliando a eficácia dos métodos de detecção atuais. A metodologia adotou uma abordagem mista, fundamentada em uma revisão sistemática da literatura conforme o protocolo PRISMA e a estratégia PICO. Foram analisados 37 artigos selecionados em bases de dados de alto impacto (Scopus, PubMed, Web of Science), filtrados de um universo inicial de 3.135 publicações. Os resultados revelam uma dicotomia espacial: áreas industriais apresentam alta incidência de metais pesados e compostos orgânicos persistentes, enquanto regiões com déficit de saneamento sofrem com contaminação microbiológica. Identificou-se uma correlação direta entre a qualidade da água e o aumento de doenças infecciosas, riscos oncológicos e resistência antimicrobiana. O estudo conclui que a gestão sustentável nas Bacias PCJ exige a implementação de monitoramento avançado e políticas públicas integradas que priorizem a proteção de populações vulneráveis e a segurança hídrica.

Palavras-chave: Bacias PCJ. Contaminantes Emergentes. Saúde Humana. Qualidade da Água. Gestão de Recursos Hídricos.

RESUMEN

Las cuencas de los ríos Piracicaba, Capivari y Jundiaí (PCJ) enfrentan desafíos críticos de seguridad hídrica debido a la intensa urbanización y a las actividades agroindustriales, que introducen una compleja carga de contaminantes en los cuerpos de agua. El problema central de investigación radica en la necesidad de comprender cómo los contaminantes emergentes (fisicoquímicos y microbiológicos) impactan la salud humana y la integridad ecosistémica, especialmente en un escenario de vulnerabilidad climática y social. El objetivo de este estudio es identificar y mapear dichos contaminantes y sus efectos en la salud pública, evaluando la eficacia de los métodos actuales de detección. La metodología adoptó un enfoque mixto, basado en una revisión sistemática de la literatura conforme al protocolo PRISMA y la estrategia PICO. Se analizaron 37 artículos seleccionados en bases de datos de alto impacto (Scopus, PubMed y Web of Science), filtrados a partir de un universo inicial de 3.135 publicaciones. Los resultados revelan una dicotomía espacial: las áreas industriales presentan alta incidencia de metales pesados y compuestos orgánicos persistentes, mientras que las regiones con déficit de saneamiento sufren contaminación microbiológica. Se identificó una correlación directa entre la calidad del agua y el aumento de enfermedades infecciosas, riesgos oncológicos y resistencia antimicrobiana. El estudio concluye que la gestión sostenible en las cuencas PCJ requiere la implementación de monitoreo avanzado y políticas públicas integradas que prioricen la protección de poblaciones vulnerables y la seguridad hídrica.

Palabras clave: Cuencas PCJ. Contaminantes Emergentes. Salud Humana. Calidad del Agua. Gestión de Recursos Hídricos.

1 INTRODUCTION

Watersheds are not only geographical drainage units, but complex systems where natural dynamics and anthropogenic pressures interact, essential for supporting ecosystems and supplying human activities (Beck, 2005; Pizella & Souza, 2013). However, rapid population growth, industrialization, and intensive agriculture have compromised the integrity of these systems. The continuous introduction of physical-chemical and microbiological contaminants, from both point sources, such as improper disposal of effluents (WHO, 2019), as well as diffuse sources, such as agricultural runoff (Khatri & Tyagi, 2015), creates a scenario of increasing risk to water security and public health (Das et al., 2019).

In the Brazilian context, this tension is exemplified in the Piracicaba, Capivari, and Jundiaí river basins (PCJ Basins), a region of high economic relevance and population density. The *2023 Status Report on the PCJ Basins* warns of worsening water vulnerability in the face of climate change, with the intensification of extreme events that concentrate pollutants and challenge conventional treatment systems. The UN's 2030 Agenda, through SDG 6, and the National Water and Basic Sanitation Agency (ANA) reinforce the urgency of ensuring universal access to drinking water and the need for strategic adaptation in the management of these resources, incorporating the analysis of emerging risks (ANA, 2024).

The persistence of traditional contaminants, coupled with the emergence of new compounds (such as pharmaceuticals and endocrine disruptors) and resistant pathogens, poses significant challenges. Studies indicate that water contamination is associated with a broad spectrum of health hazards, ranging from acute infectious diseases, such as gastroenteritis, to chronic conditions, such as cancer (Bartram, Fewtrell, & Stenström, 2001; Prüss-Ustün et al., 2019).

Given this scenario, the following research question is defined: What are the main impacts of emerging physical-chemical and microbiological contaminants on aquatic ecosystems and how do they translate into risks to human health, specifically in vulnerable contexts such as the PCJ Basins?

To answer this question, this study aims to analyze, through a systematic review of literature, the incidence and impacts of new contaminants in water systems, seeking to understand the correlations with human health. Specific objectives include mapping the main pollutants, identifying gaps in current detection methods, and assessing how these factors disproportionately affect vulnerable populations.

The rationale for this research lies in the urgent need to integrate environmental sciences and public health to support decision-making. Understanding the dynamics of contaminants in the PCJ Basins is fundamental for the development of more effective public policies and for the promotion of sustainable management technologies, in line with the guidelines of the Research Work Plan of the Dean of Research, Graduate Studies, and Extension (PROPPE) at PUC-Campinas and national water security priorities.

2 THEORETICAL BASIS

2.1 DYNAMICS AND VULNERABILITY OF WATERSHEDS

Watersheds are complex territorial units that transcend simple physical drainage. They operate as integrated systems where hydrological, ecological, and social processes are intertwined (Beck, 2005; Pizella & Souza, 2013). In the context of the PCJ Basins, this complexity is exacerbated by dense urbanization and intensive agro-industrial activities, which drastically alter the hydrological cycle and water quality. Contemporary literature emphasizes that water security depends not only on quantity but intrinsically on the quality of available resources (Vörösmarty et al., 2010), with basins being the final recipients of anthropogenic pressures that threaten biodiversity and ecosystem services.

2.2 TYPOLOGY AND ORIGIN OF CONTAMINANTS

The degradation of water quality in basins results from the cumulative interaction of point and diffuse sources of pollution.

- **Point Sources:** These are characterized by identifiable discharges, such as industrial effluents and inadequately treated domestic sewage (WHO, 2019). In the PCJ basins, solid waste disposal and the presence of contaminated areas (such as old landfills and cemeteries) represent critical vectors for the leaching of pollutants into groundwater and surface water (Cao et al., 2018).
- **Diffuse Sources:** These represent a greater challenge for monitoring and control. Surface runoff in agricultural areas carries nutrients (nitrogen and phosphorus) and pesticides, while diffuse urban drainage transports heavy metals and hydrocarbons (Khatri & Tyagi, 2015). Atmospheric deposition of industrial and vehicular pollutants completes this contamination cycle (Hu et al., 2017).

2.3 CONTAMINANTS OF EMERGING CONCERN (CECS) AND PHYSICOCHEMICAL CONTAMINANTS

The state of the art in environmental toxicology highlights the ubiquitous presence of Contaminants of Emerging Concern. In addition to classic pollutants such as heavy metals (mercury, lead, cadmium) and hydrocarbons, there is a growing detection of pharmaceuticals, personal care products, hormones, and microplastics in water bodies (Yin, Gao, & Fan, 2011). These compounds, often unregulated, have the potential for bioaccumulation and endocrine disruption in aquatic fauna, with long-term effects on human health not yet fully understood (Vázquez-Tapia et al., 2022). Eutrophication, driven by excess nutrients, remains a chronic problem, compromising potability and increasing treatment costs.

2.4 MICROBIOLOGICAL RISKS AND PUBLIC HEALTH

Microbiological contamination remains a key determinant of global morbidity. The presence of fecal indicators (such as E. coli) signals the risk of enteric pathogens, including bacteria (Salmonella spp., Vibrio cholerae), viruses (rotavirus, enterovirus), and protozoa (Giardia, Cryptosporidium) (Mbanga et al., 2020). However, current knowledge warns of an emerging and critical risk: antimicrobial resistance. Aquatic environments impacted by hospital and domestic sewage act as reservoirs of resistance genes, facilitating the spread of "superbugs" (Herrig et al., 2020). This interface between poor sanitation and microbial evolution represents one of the greatest threats to public health in the 21st century.

2.5 CLIMATE CHANGE AND HEALTH INEQUALITY

The intersection between climate and water quality is a priority field of study. Semenza & Ko (2023) demonstrate that global warming and changes in precipitation patterns directly influence the ecology of waterborne pathogens. Extreme events, such as prolonged droughts (which concentrate pollutants) and severe floods (which disperse contaminants and overload sanitation systems), exacerbate health risks. Furthermore, the distribution of these impacts is not equitable. Vulnerable populations with poor sanitation infrastructure suffer disproportionately from waterborne diseases and exposure to toxins, creating a scenario of environmental injustice (Prüss-Ustün et al., 2019). Therefore, the management of the PCJ Basins must necessarily integrate epidemiological, climatic, and hydrological data to formulate resilient and inclusive adaptation strategies.

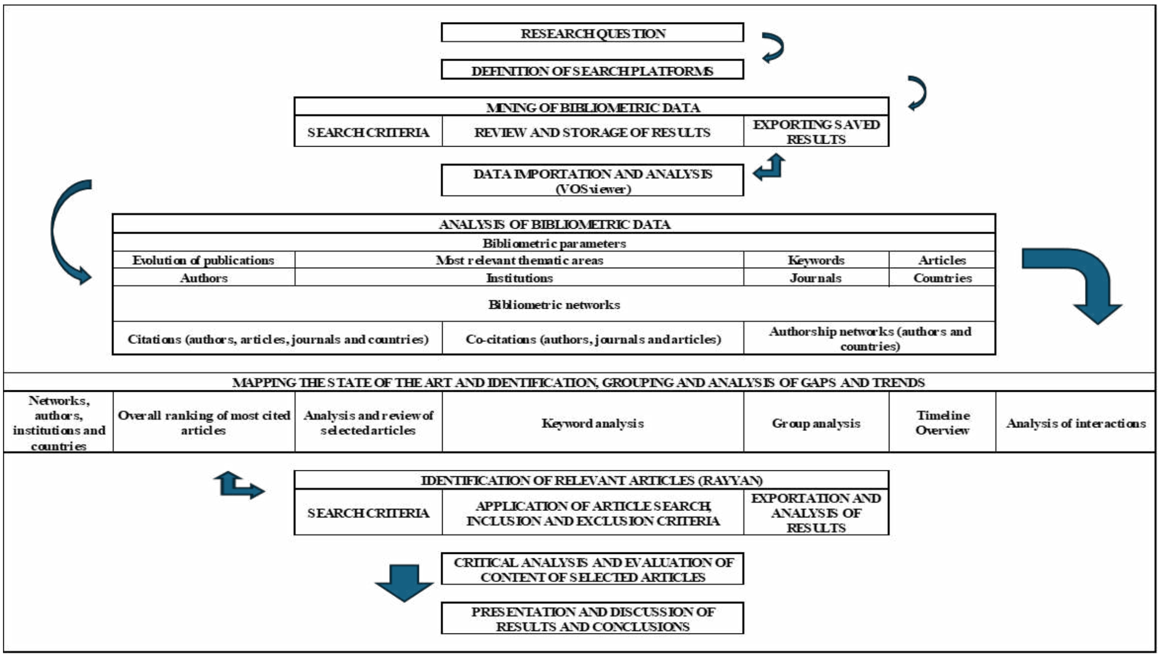
3 METHODOLOGY

3.1 RESEARCH CHARACTERIZATION AND METHODOLOGICAL APPROACH

This research adopts an exploratory and descriptive approach, seeking an in-depth understanding of the complexity of water systems and the impacts of contaminants on human health and aquatic ecosystems in the Piracicaba, Capivari, and Jundiaí River Basins (PCJ) (Creswell & Clark, 2015; Köche, 2016). A mixed methods methodology was employed, integrating elements of qualitative and quantitative analysis (Figure 1). Qualitative analysis allowed for the exploration of perceptions and experiences, while quantitative analysis enabled the identification of patterns and statistical relationships between the parameters evaluated (Creswell & Clark, 2015). Its analytical nature sought to establish causal relationships and interpret the data for a comprehensive understanding of the sources, transport, destination, and effects of contaminants (Becker, 2021).

Figure 1

Methodological flowchart



Source: Elaborated by authors, 2025

3.2 SEARCH STRATEGY AND BIBLIOGRAPHIC SELECTION: PRISMA PROTOCOL AND PICO MODEL

The collection of primary data for this review was based on a systematic search of the scientific and technical literature, strictly following the guidelines of the PRISMA protocol (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) (Galvão, Pansani & Harrad, 2015). The research question was formulated using the acronym PICO (*Population, Intervention, Comparison, Outcome*) to guide the search and selection of articles:

- **Population (P):** Watersheds, focusing on aquatic ecosystems and vulnerable human populations exposed to water risks.
- **Intervention (I):** Presence and monitoring of emerging contaminants (physical-chemical and microbiological).

- **Comparison (C):** Studies comparing different geographical contexts, types of contamination sources, and methodological approaches.
- **Outcome (O):** Impacts on human health (infectious diseases, cancer, antimicrobial resistance) and effects on aquatic ecosystems (biodiversity degradation, eutrophication).

The systematic search was conducted in the following high-impact and multidisciplinary databases: *Scopus*, *Web of Science*, *PubMed,* and *ScienceDirect*. To optimize search sensitivity, keywords and their synonyms were used in combination with Boolean operators (AND, OR), such as: ("water" OR "aquatic ecosystems") AND ("contaminants" OR "pollutants" OR "emerging contaminants") AND ("health" OR "human health" OR "public health") AND ("watershed" OR "river basin").

The article selection process involved the following steps:

1. **Identification:** Initial prospecting of 3,135 articles in the database.
2. **Screening:** Loading of references into the *Rayyan* application to eliminate 1,769 duplicates. *Rayyan* uses artificial intelligence algorithms to assist in the prioritization and classification of articles during the screening of titles and abstracts, increasing the efficiency of the process and initial consistency. This step resulted in 1,366 articles for in-depth analysis.
3. **Eligibility:** Blind (double-blind) application of inclusion criteria (relevance to the theme of water contamination, human health, and water resource management) and exclusion (studies not primarily focused on emerging contaminants or health impacts, undetected duplicates, articles in irrelevant languages, or articles that did not pass the initial filters), resulting in the selection of 37 articles for full review.

3.3 DATA COLLECTION AND ANALYSIS FROM THE SELECTED LITERATURE

From the 37 selected articles, data collection, processing, and analysis were organized into interrelated steps to obtain comprehensive information on the impacts of contaminants in watersheds, according to the PICO model:

3.3.1 Types of Contaminants Identified (Population/Intervention):

The nature of the contaminants (physical chemical such as heavy metals, POPs, pesticides, pharmaceuticals, PFAS, and parabens; and microbiological such as pathogenic bacteria, viruses, protozoa), their concentrations, and the reported frequency of occurrence were investigated. The sources of contamination (point vs. diffuse) were classified based on the information presented in the studies, considering factors such as industrial discharges, domestic sewage, agricultural runoff, and atmospheric deposition. The analysis sought to highlight their characteristics and relevance to water contamination.

3.3.2 Methods Used in Studies (Intervention):

Water sampling methodologies and analytical techniques used for the detection and quantification of contaminants were analyzed. This included the identification of laboratory methods (e.g., PCR, microbiological culture, mass spectrometry) and modeling and statistical approaches. The objective was to evaluate the effectiveness and applicability of these techniques in detecting emerging and traditional contaminants.

3.3.3 Observed Impacts (Outcomes):

Human health outcomes were categorized based on epidemiological studies, seeking associations between exposure to contaminants and the occurrence of health problems, including infectious diseases (gastroenteritis, hepatitis, cholera), cancer (associated with prolonged exposure to carcinogens), and antimicrobial resistance. At the same time, the effects on aquatic ecosystems were assessed, considering biodiversity degradation, bioaccumulation, and eutrophication.

3.3.4 Comparison between Contexts and Approaches (Comparison):

A comparative analysis was performed to identify significant differences in contaminant profiles and impacts between different geographical contexts (urban/industrial vs. rural/poor sanitation) and in the methodological approaches employed. This allowed us to correlate contaminant distribution patterns with their sources and environmental factors that influence their transport and transformation.

3.4 USE OF ARTIFICIAL INTELLIGENCE TOOLS:

Throughout the research process, Artificial Intelligence (AI) tools, specifically Large Language Models (LLMs), were used to optimize certain review and writing steps. In accordance with the journal's policy, we inform you that Rayyan's internal AI feature was used to assist in the preliminary screening of abstracts to accelerate the identification of exclusion criteria (e.g., incorrect publication type). However, all final inclusion/exclusion decisions were manually verified by the authors. Generative AI (Gemini 2.5) was used exclusively for linguistic review and to assist with the translation of the manuscript. LLMs were used for:

1. **Preliminary summarization:** Assist in the synthesis of extensive sections of

ISSN: 2177-3246

selected articles, facilitating the extraction of the most relevant information for the topic.

2. **Identification of terms and synonyms:** Suggest additional search terms to refine search equations in databases.
3. **Refinement of language and textual clarity:** Contribute to the rewriting of paragraphs, improving conciseness, cohesion, and adherence to the academic style required by high-impact journals.

It should be noted that the application of these tools was always supervised and validated by the research team, ensuring that human discernment and specialized knowledge prevailed over the suggestions generated by AI. The main objective of using AI was to increase efficiency and consistency in the manipulation of large volumes of information, without replacing the critical and interpretive analysis of the researchers.

3.5 CONTRIBUTION TO KNOWLEDGE AND SUGGESTIONS FOR FUTURE RESEARCH

The final stage consisted of synthesizing the findings to identify the main gaps in scientific knowledge and the implications of the results for water resource management. Based on this, recommendations were developed for the implementation of mitigation measures and directions for future research were suggested, aiming to deepen knowledge and develop innovative and sustainable solutions for PCJ Basins.

3.6 ETHICAL PROCEDURES

Considering that the research is based exclusively on a systematic review of published literature and the analysis of secondary data in the public domain, without the collection of data from humans or animals, approval by Research Ethics Committees (RECs) is not required, in accordance with current regulations for studies of this nature.

4 RESULTS AND DISCUSSION

This section presents the main findings of the systematic review of the literature and discusses their implications for understanding the impacts of emerging contaminants on human health and aquatic ecosystems in the PCJ Basins.

4.1 LITERATURE SEARCH AND SELECTION PROCESS

The search strategy, guided by the PICO model and the PRISMA methodology, began with the prospecting of 3,135 articles in the *PubMed*, *ScienceDirect*, and *Scopus* databases (Figure 2). The rigorous screening process, which included the elimination of

1,769 duplicates via the *Rayyan* application (software that uses AI algorithms for pre-screening), resulted in 1,366 articles for initial analysis. After blind application of the inclusion and exclusion criteria, 37 articles were considered eligible for in-depth systematic review.

Figure 2

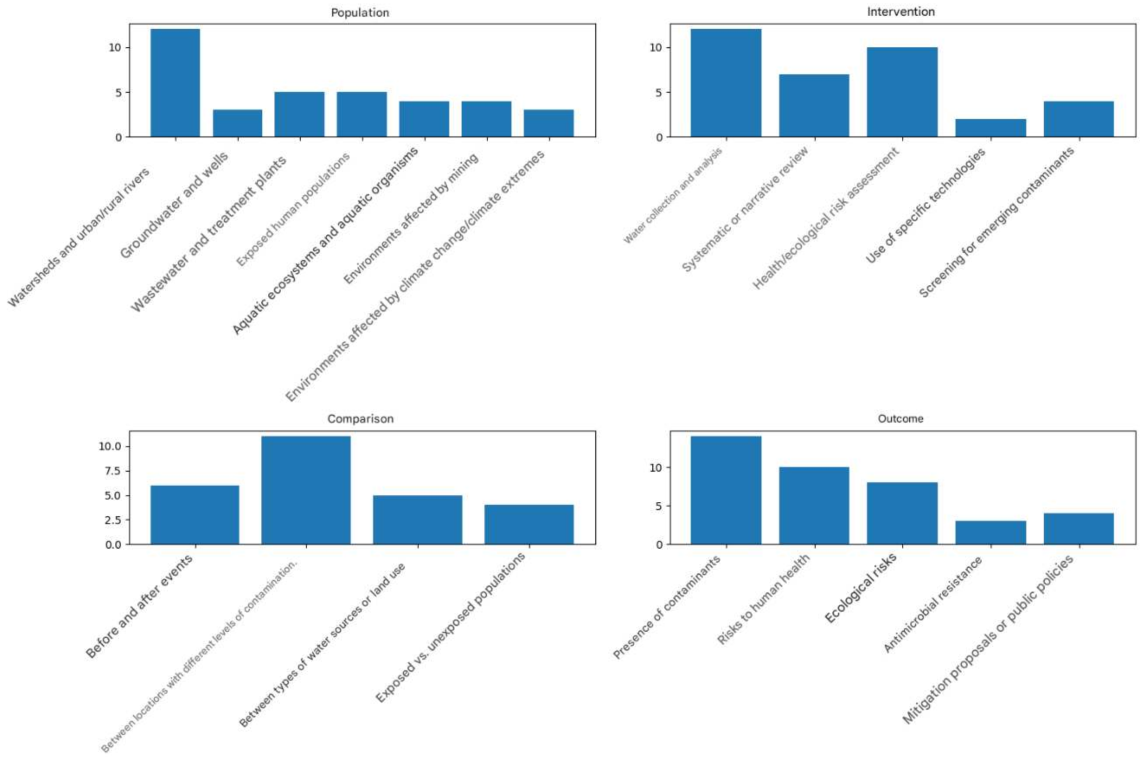
Boolean search equation used in the systematic review

("water" AND ("contaminants" OR "pollutants") AND ("physical-chemical" OR "chemical" OR "microbiological" OR "microbial")) AND ("contaminants" OR "pollutants") AND ("watersheds" OR "river basins" OR "drainage basins") AND ("environmental consequences") AND ("health" OR "human health" OR "public health" OR "health effects") AND ("aquatic ecosystems" OR "aquatic environments" OR "aquatic life") AND ("water quality" OR "water pollution" OR "water contamination") AND ("ecotoxicology" OR "toxic effects")

Source: Elaborated by authors, 2025.

Figure 3

Distribution of selected articles according to PICO components



Source: Elaborated by authors, 2025.

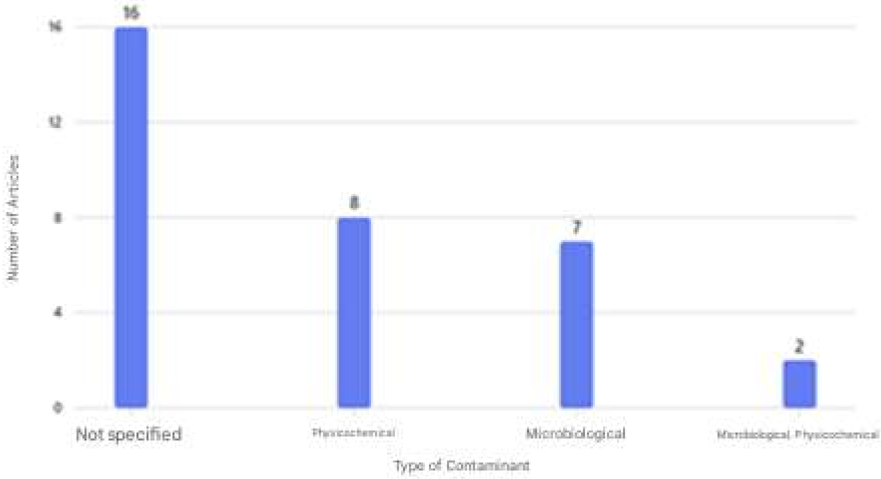
Figure 3 shows the distribution of articles according to the PICO categories, emphasizing that the selected studies address diverse populations, focusing on interventions related to the identification of contaminants and a variety of health and ecosystem outcomes.

4.2 TYPES OF CONTAMINANTS IDENTIFIED

The analysis of the 37 studies revealed a predominance in the approach to **physical-chemical contaminants**, followed by **microbiological contaminants**. The most frequently reported physical-chemical pollutants include heavy metals (mercury, lead, cadmium), persistent organic pollutants (POPs), pesticides, pharmaceuticals, and new classes of substances such as PFAS and parabens. In contrast, microbiological contaminants include pathogenic bacteria (*E. coli*, *Salmonella spp.*), viruses, and protozoa, with relevance in scenarios of poor sanitation and after extreme events (floods).

Figure 4

Percentage distribution of the types of contaminants addressed in the selected articles



Source: Elaborated by authors, 2025.

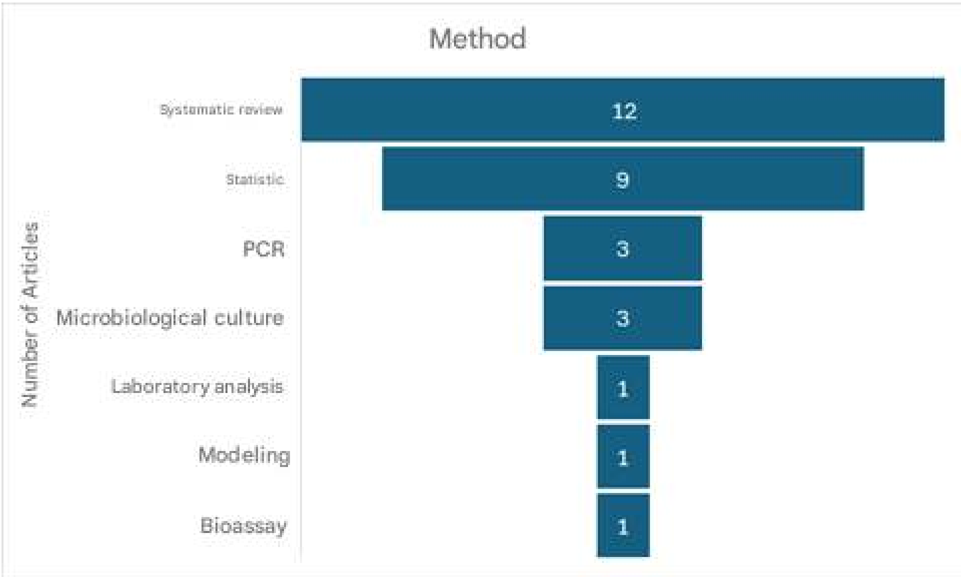
Figure 4 clearly illustrates the greater representation of physical-chemical contaminants in the reviewed literature, which may reflect the growing concern with emerging substances and their complexity in terms of detection and toxicology.

4.3 METHODS USED IN STUDIES

The methodological diversity in the selected studies underscores the complexity inherent in water contamination research. The most prevalent methods were statistical analyses (used for modeling and data correlation), laboratory techniques such as PCR (Polymerase Chain Reaction) and microbiological culture, and systematic reviews (to synthesize evidence). Bioassays to assess toxicity were also identified.

Figure 5

Frequency of methods of analysis used in the selected studies



Source: Elaborated by authors, 2025.

Figure 5 highlights that combining different approaches is essential for a holistic understanding of phenomena. Advanced methods such as PCR and mass spectrometry (often associated with "laboratory techniques" and "statistical analyses") are crucial for detecting emerging contaminants at low concentrations and assessing risks more accurately.

4.4 OBSERVED IMPACTS (OUTCOMES)

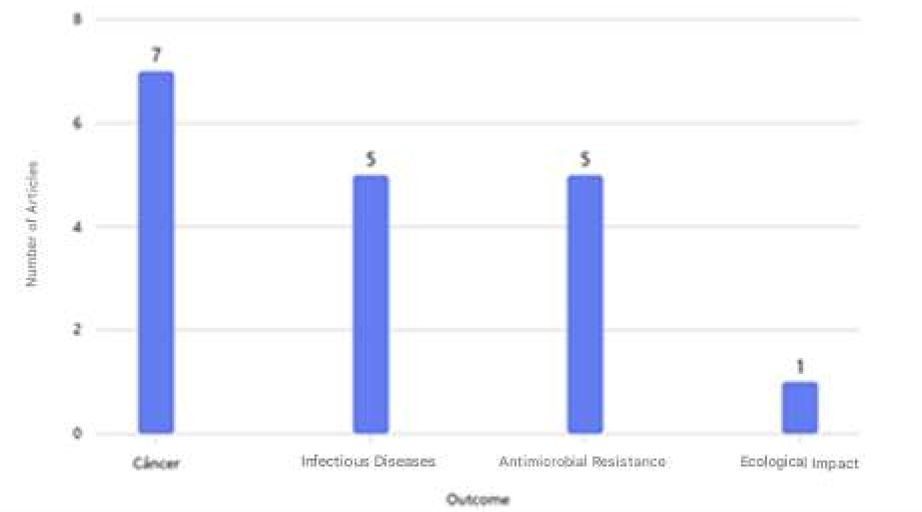
The effects of contamination were categorized into four main outcomes, highlighting the breadth of health and environmental problems:

1. **Ecological Impacts:** These include the degradation of aquatic biodiversity, the bioaccumulation of pollutants in organisms, and the eutrophication of water bodies. These impacts affect the integrity of the ecosystem and, consequently, the availability of quality water.
2. **Infectious Diseases:** These are most directly related to microbiological contamination, such as gastroenteritis, hepatitis, and cholera, which pose acute risks to human health, especially in vulnerable populations with poor sanitation (Bartram, Fewtrell, & Stenström, 2001; Prüss-Ustün et al., 2019).
3. **Cancer:** Associated with prolonged exposure to carcinogenic contaminants, such as some heavy metals and persistent organic compounds, as reported in several studies.
4. **Antimicrobial resistance (AMR):** The presence of antibiotics and resistance genes

in aquatic environments is an emerging outcome of great global concern (Herrig et al., 2020), indicating that watersheds can act as reservoirs and vectors for the spread of AMR.

Figure 6

Frequency of types of outcomes identified in the selected articles



Source: Elaborated by authors, 2025.

4.5 DISCUSSION: CORRELATION BETWEEN CONTAMINANTS, METHODS, AND IMPACTS IN THE PCJ BASINS

The analysis of the 37 studies identified significant differences between geographical contexts and methodological approaches, with direct implications for the PCJ Basins. Studies conducted in urban and industrialized regions, the predominant scenario in most of the PCJ Basins, showed a higher prevalence of physical-chemical contaminants (e.g., heavy metals, POPs, PFAS), often associated with industrial and urban effluents (Hu et al., 2017). In contrast, rural areas or areas with poor sanitation, which also exist extensively in the PCJ region, showed a higher incidence of microbiological contaminants and the occurrence of infectious diseases, corroborating the vulnerability of communities with limited access to adequate infrastructure (Mbanga et al., 2020).

The effectiveness of detection methods proved to be a critical factor. Studies using advanced laboratory techniques, such as PCR and mass spectrometry, were more successful in identifying emerging contaminants, such as pharmaceuticals and perfluoroalkyl substances, and in assessing risks to human health at subclinical concentrations. The application of these technologies in the PCJ Basins is essential for more accurate monitoring and early risk identification, overcoming the limitations of traditional methods that may underestimate the actual pollutant load. Statistical modeling, in turn, contributed to the understanding of distribution patterns and correlations between environmental factors, sources of origin, and contamination levels, a vital aspect for the integrated management of the PCJ.

The observed outcomes reinforce the urgency of comprehensive water management. The presence of ecological impacts, such as eutrophication and biodiversity degradation, directly impacts the ability of watersheds to provide drinking water and maintain their ecosystem services. The occurrence of infectious diseases and the risk of cancer, predominant in studies focused on vulnerable communities and areas with a history of pollution, confirm the need for public policies that address social justice and environmental equity in the distribution of basic sanitation services. Notably, the emergence of antimicrobial resistance as a relevant outcome in the reviewed literature highlights the need to integrate the "One Health" perspective into the management of water resources in the PCJ Basins, recognizing the interconnection between environmental, animal, and human health (Prata, 2022).

The reviewed literature, aligned with the reality of the PCJ Basins, demonstrates that water contamination is a multifaceted problem that requires multidisciplinary approaches. The research question about the impacts of emerging contaminants on human health is answered by evidence that these pollutants contribute to a spectrum of diseases, from acute infections to chronic diseases and the spread of antimicrobial resistance. The need to improve detection methods and consider the local socio-environmental context are imperative for more effective and protective management.

5 CONCLUSIONS

This study undertook a comprehensive systematic review to investigate the impacts of emerging contaminants, both physicochemical and microbiological, on watersheds and their direct effects on human health and aquatic ecosystems. The overall objective of identifying, through a systematic review of the literature, new physicochemical and microbiological contaminants present in aquatic systems and their potential impacts on human health was fully achieved. The in-depth analysis of the 37 selected scientific articles made it possible to map the main pollutants, correlate their presence with various health and environmental outcomes, and identify critical gaps in detection methods.

The research confirmed that the simultaneous presence of physicochemical contaminants (heavy metals, persistent organic pollutants, pesticides, pharmaceuticals, PFAS, and parabens) and microbiological contaminants (pathogenic bacteria, viruses, protozoa, and, critically, antimicrobial genes) in river basins represents a complex management challenge and a multifaceted risk to public health. This complexity is particularly pronounced in densely populated and economically active regions, such as the Piracicaba, Capivari, and Jundiaí (PCJ) river basins, where anthropogenic pressures intensify the pollutant load and exacerbate water vulnerability.

The methodological analysis highlighted the indispensability of advanced analytical techniques, such as PCR and mass spectrometry, for the effective detection of emerging contaminants at low concentrations and for the accurate assessment of risks to human and ecological health. Reliance on traditional methods may underestimate the true extent of the problem, especially for hard-to-detect pollutants and emerging or resistant pathogens.

The identified outcomes—from biodiversity degradation and eutrophication to the incidence of infectious diseases, cancer risks, and, notably, the spread of antimicrobial resistance, demonstrate the critical interconnection between ecosystem health and human health. This spectrum of impacts reinforces the urgent need for a holistic approach, based on the concept of "*One Health*," for water resource management. The differences in contamination profiles between urban/industrial areas and rural areas with poor sanitation underscore that management strategies and public policies must be contextualized and adapted to local realities within the PCJ Basins, aiming to mitigate disproportionate impacts on vulnerable populations.

In short, this research contributes significantly to the growing body of knowledge on water contamination and its impacts. The results provide valuable insights for water resource managers, public policy makers, and health professionals in the PCJ Basins, pointing to the urgency of strengthening continuous monitoring programs, improving basic sanitation infrastructure, and developing more robust and preventive regulations for emerging contaminants. The integration of technical, epidemiological, and social knowledge is crucial in the search for sustainable solutions that guarantee water quality and availability.

6 STUDY LIMITATIONS

Despite the advances provided by this systematic review, it is important to recognize its limitations. The main limitation lies in the dependence on the quality, scope, and methodological heterogeneity of the published literature. Although we employed a rigorous selection protocol (PRISMA), the variability in sampling methods, laboratory analyses, and presentation of results in the primary studies may hinder direct comparisons and the generalization of certain findings. Additionally, as this research is a literature review, it does not generate specific primary data from the PCJ Basins, which prevents a direct and detailed empirical assessment of the incidence and distribution of contaminants and diseases in the region, depending on the availability of previously published local studies. The inclusion of secondary data in the public domain minimized this limitation by contextualizing the global findings.

7 SUGGESTIONS FOR FUTURE WORK

To deepen understanding of the issue and support more effective actions in the PCJ Basins, we suggest the following lines of future research:

1. **Local Field Studies:** Conducting primary field studies in the PCJ Basins to quantify the occurrence and distribution of emerging contaminants and their direct impacts on local communities and ecosystems, filling the gaps identified by this review.
2. **Treatment and Monitoring Technologies:** Evaluate the applicability and cost-effectiveness of advanced treatment technologies for emerging contaminants (e.g., microplastics, PFAS) and real-time monitoring systems at treatment plants and water bodies in the region.
3. **Integrated Predictive Modeling:** Development of predictive models that integrate water quality data, public health (SINAN), climate change and Socioeconomic scenarios for the PCJ Basins, to support strategic planning and the identification of priority risk areas.
4. **Water Justice and Governance:** Investigation of the socioeconomic and governmental aspects of contamination, with a focus on water justice, environmental equity, and participatory governance mechanisms for the basins, involving civil society and local actors in water resource management.
5. **Intervention Studies:** Conducting intervention studies to assess the effectiveness of mitigation measures and environmental sanitation technologies adapted to the specificities of the region, such as ecological sanitation, restoration of riparian forests, and sustainable agricultural practices.

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