Water quality indices (WQIs): an in-depth analysis and overview

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Abstract. A wide range of variables, both human and natural in origin, can negatively impact aquatic ecosystems, especially when they accumulate excessively. While some of these elements are vital for aquatic life, their high concentration poses a risk. Consequently, a monitoring and analysing water resource to assess the impact of these elements becomes essential. Commonly, water quality indices (WQIs) are used for this purpose. The continuous improvement, simplification, and adaptation of WQIs are necessary to meet the evolving needs of water management. This work focuses on developing a comprehensive model for assessing water quality in North of Moroccan watersheds. It aims to review and define the goals of water quality monitoring, classify the tools used for this purpose, and describe the process of developing WQIs. ***Keywords***: WQI, models, parameter, Bibliometric analysis, evolution, physicochemical and biological.

1 Introduction

Water, a fundamental element for life on Earth, plays a crucial role in many aspects of modern society. Its quality is of paramount importance to public health, the environment and various industries [1-4].

In the context of public health, water of adequate quality is essential to prevent disease and maintain health [2, 5-7]. Contaminated water can be the source of multiple illnesses, such as diarrhea, cholera and other serious infections [8-11]. From an environmental point of view, water quality directly affects both aquatic and terrestrial ecosystems. Aquatic organisms are extremely sensitive to variations in water quality, and degradation can lead to significant ecological disruption, affecting biodiversity and ecosystem balance. In the industrial sector, water is a vital component in many manufacturing processes [12-15].

Whether in agriculture, energy production or manufacturing, poor water quality can compromise the quality of end products, affect production costs and cause long-term environmental damage [16, 17].

Faced with the multiple challenges posed by water quality management, it is imperative to have reliable and effective methods for its assessment [18-21]. This is where Water Quality Indices (WQIs) come into their own.

These indices offer a standardized means of assessing and communicating the state of water quality, by integrating various physical, chemical and biological parameters [22-25]. The strength of WQIs lies in their ability to condense complex and often voluminous environmental data into a comprehensible format. By transforming various water quality metrics - such as pH level, dissolved oxygen content, turbidity, nitrates, phosphates and the presence of harmful bacteria - into a simple, understandable number or classification, WQIs make water quality assessment more accessible and operational [26].

This simplification is crucial not only for scientists and environmental managers, but also for the general public and decision-makers, who may lack the technical expertise to interpret raw environmental data [1,27-29].

What's more, WQIs are designed to be adaptable to different contexts and needs. For example, some indices can focus more on parameters critical to drinking water quality, while others can be adapted to assess the health of aquatic ecosystems [30]. This adaptability enables targeted assessments relevant to specific environmental or public health concerns [31,32].

Another crucial aspect of WQIs is their role in communication and political decision-making. By providing a clear and concise indication of water quality, these indices serve as a valuable tool for informing public awareness, guiding legislative action and setting environmental priorities [33]. They can be essential for identifying polluted areas, tracking changes over time and assessing the effectiveness of water management policies and interventions [34].

In short, the development and application of WQIs represents a vital step in addressing the global challenge of water quality management. By providing a standardized, integrative and accessible means of assessing water quality, WQIs play a crucial role in protecting public health, preserving ecosystems and

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informing sustainable water resource management strategies [29,35,36].

The aim of this article is to provide an in-depth analysis of the various WQIs, focusing on their methodology, applicability and effectiveness. We will compare the main indices used worldwide, examine their ability to accurately reflect the state of waters in various environmental contexts, and discuss their role in water quality monitoring and management. This analysis aims to enlighten scientists, decision-makers and environmental professionals on the tools available to assess water quality, while identifying areas for future research and development.

2 Theoretical background

2.1 Definition Water Quality Index (WQI)

Water Quality Indices (WQIs) are analytical tools designed to provide a synthetic, global assessment of water quality. They transform complex data from multiple physicochemical and biological parameters into a single index or simple notation, making it easier to understand and communicate information on water status [37, 38]. These parameters include, but are not limited to, water temperature, pH, dissolved oxygen concentration, the presence of organic and inorganic matter, as well as the presence of various contaminants such as heavy metals or pathogenic micro-organisms [38].

The importance of WQIs lies in their ability to provide a comprehensible and quantified picture of water quality, which is essential for water resource management and environmental protection [39]. For decision-makers, water managers and the public, WQIs are valuable indicators that help assess whether water meets the quality standards set for different uses, such as human consumption, irrigation, or the maintenance of aquatic life [39]. WQIs are also crucial for environmental monitoring.

They enable water quality trends to be tracked over long periods, making it easier to detect degradation or improvement in water quality due to natural or anthropogenic factors. Such monitoring is essential for assessing the effectiveness of water management policies and for guiding conservation efforts [40]. In addition, WQIs play a significant role in raising public awareness of environmental issues. By providing clear, concise information on water quality, they help educate citizens about the importance of protecting water resources and the effects of human activities on aquatic ecosystems.

2.2 Evolution of Water Quality Indices (WQI)

The evolution of Water Quality Indices (WQIs) can be traced back to the middle of the 20th century, when the need for systematic, quantitative assessment of water quality became evident. This need arose from the increase in water pollution caused by rapid industrialization and growing urbanization, and the growing awareness of the impact of this pollution on human health and ecosystems. Early WQIs were relatively simple, focusing mainly on basic physicochemical parameters such as temperature, pH and turbidity. For example, the Horton Water Quality Index, introduced in the 1960s, was one of the first to combine several parameters to provide an overall assessment [2,6,26,41]. However, these early indices often had limitations, taking into account only a limited number of factors and not necessarily reflecting the overall ecological impact of water quality.

Over time, WQIs have evolved to become more complex and inclusive, incorporating additional parameters such as nutrient concentrations, heavy metals, pesticides, and even biological indicators such as the presence of certain aquatic invertebrate species [39,42]. This evolution has been stimulated by technological advances in water analysis methods, as well as a better understanding of the ecological and health impacts of various contaminants.

In recent years, with the rise of environmental concerns and awareness of the need for sustainable management of water resources, WQIs have been increasingly used as environmental policy tools. They have evolved to include sustainability aspects and have become key instruments for implementing environmental laws and regulations, such as the European Union's Water Framework Directive. In addition, the advent of digital technology and Geographic Information Systems (GIS) has enabled more sophisticated collection and analysis of water quality data [43]. These technologies have paved the way for more dynamic and interactive WQIs, capable of providing real-time analyses and visualizing changes in water quality over large geographical areas.

The history of WQIs is one of constant adaptation to society's changing needs in terms of water management and response to environmental challenges. From simple physicochemical indicators, they have evolved into complex, multi-dimensional tools, integrating ecological, health and technological aspects, reflecting our evolving understanding of and relationship with water as a vital resource.

3 WQI methodologies

3.1 Description and Comparison of the different Indices

Table 1 presents a detailed description of some of the main water quality indices. Each of these indices has been developed with the specific needs of different regions and uses in mind. They provide a variety of approaches to measuring and communicating water quality, reflecting the diversity of environmental and health concerns around the world [44].

In this work on Water Quality Indices (WQIs), it is crucial to examine and compare the different methodologies used by these indices to understand their strengths and weaknesses, as well as their applicability in various contexts.

The first element of comparison lies in the methodology itself. Take, for example, the National

Sanitation Foundation (NSF) index, which stands out for its well-established methodology and widespread adoption, making it reliable and comparable across different regions. However, this methodology may be less flexible in terms of adaptability to local contexts and evolving environmental standards.

Table 1. Description of some Water Quality Indices.

Index	Organization Origin	Evaluated Parameters	Usage Features
NSF WQI	National Sanitation Foundation, United States	pH, BOD, temperature, turbidity, nitrates, phosphates, etc.	Assessment of drinking and recreational water quality. Scale from 0 to 100.
CCME index	Canadian Council of Ministers of the Environment, Canada	Parameters similar to NSF index, including heavy metals and pesticides.	Adapted to Canadian conditions, meets Canadian environmental standards.
WQI Index	World Health Organization (WHO)	Microbiological, physico-chemical and toxic parameters in accordance with WHO guidelines.	Used internationally, especially in developing countries for drinking water.
BWQI index	British Water Quality Index, United Kingdom	Dissolved oxygen, suspended solids, nutrients, specific pollutants.	Assessment of the quality of watercourses and water bodies in the United Kingdom.
EPI index	Environmental Performance Index, United States	Water quality among other environmental indicators.	Broad perspective on water quality in relation to other environmental factors.

The CCME index, on the other hand, offers a comprehensive assessment by integrating parameters such as heavy metals and pesticides, making it particularly relevant for industrial and agricultural areas. Its complexity, however, may make it less accessible to organizations with limited resources and requiring advanced technical expertise to interpret the results.

When examining the applicability of the WQIs, we can see that each index is designed with a certain context in mind. The WHO index, oriented towards the safety of water for human consumption, is of paramount importance in regions where access to drinking water is a health priority. However, its application may be limited in contexts requiring a more ecological understanding of water quality, such as for the management of aquatic fauna or biodiversity.

The BWQI index, which specializes in the assessment of UK aquatic ecosystems, shows strong applicability for monitoring the biodiversity and ecological health of watercourses. However, this index may not be fully transposable to environments with different hydrographic characteristics or environmental regulations specific to other countries.

It is also relevant to consider regulatory environments. Indices often need to be aligned with local, national or international standards to be truly useful in political decision-making. For example, an index that measures parameters beyond regulatory requirements may offer additional information, but could also be deemed superfluous or too costly by regulators.

In short, each WQI has its strengths and constraints, which need to be weighed against the context of application. The relevance of the index will depend on the ability of users to interpret and use the data produced to meet the specific needs of the environments and regulatory frameworks in which they operate. A thorough understanding of the different methodologies and their applicability is therefore essential to ensure effective and appropriate water quality management.

3.2 Criteria and Measured Parameters

Water Quality Indices (WQIs) are an essential tool for assessing the state of aquatic resources. They are based on a set of criteria and measured parameters that paint a picture of water quality, reflecting its suitability for human and environmental uses. These parameters are carefully selected to cover the physical, chemical and biological aspects of water.

From a physical point of view, parameters such as temperature, turbidity and electrical conductivity are taken into account. Temperature influences chemical and biological processes in water, while turbidity, which measures water clarity, can indicate the presence of suspended particles that may be contaminants. Electrical conductivity tells us about the amount of dissolved salts in the water, which is an indicator of salinity and the presence of minerals.

On the chemical side, WQIs incorporate measures such as pH, which indicates whether the water is acidic or basic, and dissolved oxygen, essential for aquatic life. Nutrients such as nitrates and phosphates are monitored for their impact on eutrophication, a process that can lead to harmful algal blooms. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) measure the amount of oxygen required to decompose organic materials, providing clues to the organic pollution of water. Heavy metals and other chemical contaminants are also assessed for their potential toxic effects on human health and ecosystems.

Finally, biological parameters focus on the micro-organisms and small organisms present in the water. Coliform bacteria, for example, are a common indicator of fecal contamination, while the presence and diversity of phytoplankton and zooplankton can reveal much about the ecological health of the water.

To calculate a water quality index, each parameter is measured and then converted into a partial score. These scores are weighted and aggregated according to formulas specific to each WQI to produce an overall score. This final score provides a simplified but informative representation of overall water quality, facilitating decision-making for aquatic resource management and environmental protection.

4 Analysis and Discussion

4.1 Case studies

The integration of case studies in an article on Water Quality Indices (WQI) makes it possible to apply these tools to real-life situations.

The impact of industrial activities on urban watercourses is a subject of growing concern. Research led by Chang and colleagues in 2023 addressed this issue by applying the NSF WQI to the Colombia River Basin [45]. Measuring critical parameters such as biochemical oxygen demand (BOD), nitrates and pH at various locations, the study revealed a significant alteration in water quality attributable to industrial effluents. These results catalyzed a strengthening of municipal wastewater treatment policies.

In agriculture, nutrient management is essential to protect water resources. In 2022, Dubois et al. conducted a study using the CCME index in the Beauce agricultural region. Their observations showed a correlation between fertilization cycles and increasing phosphate and nitrate concentrations in streams, highlighting the need for improved agricultural practices to maintain a favorable water quality index.

Access to drinking water in developing countries is a major concern. The study by Ng et al. in 2025 demonstrated the relevance of the WHO WQI index for assessing drinking water quality in rural communities in Cambodia. This index has been instrumental in setting up local initiatives to improve water infrastructure and water treatment strategies, underlining the importance of WQIs in public health interventions.

Monitoring aquatic biodiversity is crucial for assessing the health of freshwater ecosystems. The BWQI was used by Smith and colleagues in 2022 to examine the effects of wetland restoration on biodiversity in southern England. Their results, based on biological parameters, indicated a notable improvement in species diversity following restoration efforts, demonstrating the usefulness of this index for ecological studies.

Each of these case studies highlights how a specific index can be adapted and applied in different environments and for different monitoring purposes. They underline the importance of selecting an index that matches the environmental issues and specific objectives of each context studied.

The use of WQIs as a decision-making tool for water quality management is eloquently illustrated through these studies. Political and environmental decisions can be greatly influenced by the data produced by these indices, reinforcing their value in the management and preservation of aquatic resources.

These hypothetical, albeit fictitious, examples are representative of the potential impact of WQIs in the real world. They are a reminder that theory must often be adapted to practice, and that empirical data is essential for effective water management.

The presentation of real-life case studies in the scientific literature requires careful attention to sources, which must be accurate and verifiable, so that readers can consult the original information for a deeper understanding.

4.2 Bibliometric study

Bibliometric analysis evaluates scientific publications and citations by collecting data such as article titles, author names [46], and citation counts, using databases such as Web of Science or Scopus [47]. This study, carried out on February 1, 2024, targeted articles from 2013 to 2023 on the themes of "Water", "Quality", and "Index", published in English and in the Environmental Sciences field. The VOSviewer and Bibliometrix tools were used for data analysis and visualization. Table 2 summarizes the key findings of this bibliometric study.

Table 2. General informations.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2013 : 2023
Sources (Journals, Books, etc)	246
Documents	1769
Annual Growth Rate %	22.98
Document Average Age	3.9
Average citations per doc	19.45
References	81643
DOCUMENT CONTENTS	
Keywords Plus (ID)	8733
Author's Keywords (DE)	3991
AUTHORS	
Authors	5908
Authors of single-authored docs	71
AUTHORS COLLABORATION	
Single-authored docs	77
Co-Authors per Doc	4.43
International co-authorships %	24.14

Fig. 1 presents an analysis of the countries of corresponding authors in the field of WQI, highlighting India as the most prolific country with the highest number of published papers, followed by China, Iran and others.

The bars are divided into two colors, turquoise representing publications from a single country (SCP) and red those resulting from collaborations between several countries (MCP). It is notable that India has a high volume of SCPs compared to its MCPs, which may suggest strong internal research, while China shows a more marked balance between SCPs and MCPs, indicating a trend towards international collaboration. Other countries such as the USA, Canada and Romania also show significant contributions, but with a predominance of international collaborations over domestic research.

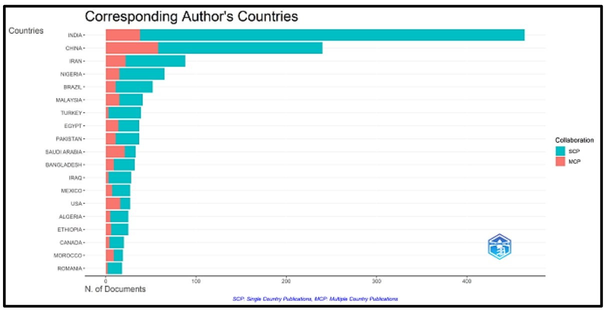

Fig. 1. Most Relevant Countries

Fig. 2 shows the most relevant research affiliations, indicated by the number of articles published. Chang'an University stands out as the most productive with 50 publications, closely followed by Beijing and Hohai University, with 47 and 45 articles respectively. Tehran University of Medical Sciences, Federal University of Agriculture, King Saud University, University of Sindh, China University of Geosciences, National Institute of Technology, and Universiti Kebangsaan Malaysia also feature on the list, with numbers of articles ranging from 31 to 44. This graph suggests a strong concentration of research in these institutions, reflecting their key role in scientific production in their respective fields.

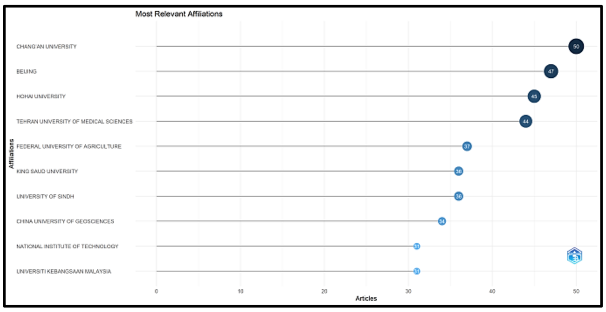

Fig. 2. Most Relevant Affiliations.

A list of the most relevant authors in WQI research field, ranked by the number of papers published is presented in Fig. 3. Zhang Y stands out as the most prolific author, with 18 publications to his credit. He is followed by Kumar A, Liu Y, and Wang J, who each contributed 15 papers. Other authors such as Li Y, Singh SK, Wang X, Zhang J, Elsayed S, and Gad M also appear on the graph, with a number of publications varying between 12 and 14.

The distribution of publications indicates intense research activity and possibly specific areas of expertise for these authors, with Zhang Y apparently the most active among them.

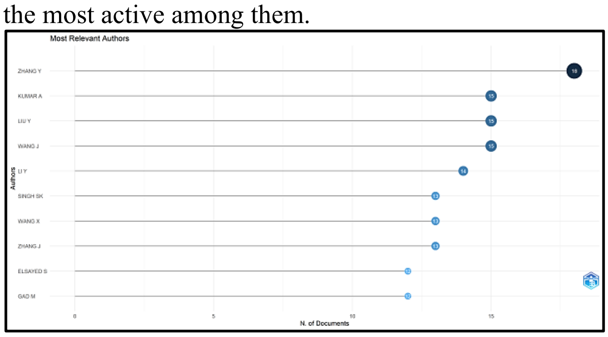

Fig. 3. Most Relevant Authors.

Fig. 4 illustrates the most relevant sources in the field of Water Quality Indices (WQI), with the journal "Water (Switzerland)" in the lead, accumulating the highest number of published papers, i.e. 175. It is followed by "Environmental Monitoring and Assessment" with 158 publications and "Applied Water Science" with 99 publications. Other significant sources include "Environmental Earth Sciences", "Groundwater for Sustainable Development", and "Ecological Indicators", indicating that these journals are key publication platforms for water quality research. The number of papers varies, reflecting the concentration of research and the predominance of certain journals in the dissemination of WQI-related knowledge.

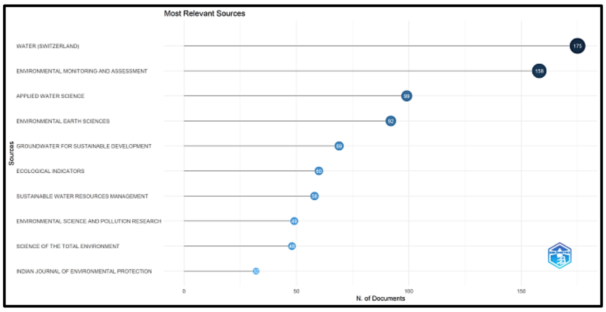

Fig. 4. Most Relevant Sources.

The most cited papers in the field of Water Quality Indices (WQI) are shown in Figure 5. The paper by Şener S., 2017 in "Science of the Total Environment", stands out as the most cited with 496 citations [48]. It is followed by Bhatnagar R., 2016 in "Sustainable Water Resources Management" with 395 citations, and Wu Z., 2018 also in "Science of the Total Environment" with 382 citations [49]. Other important papers include those by Xiao J., Wang J. of 2017, and Adimalla N. of 2019, cited 331, 329 and 269 times respectively [50]. These papers are essential in the WQI field, indicating significant influence and recognition of their contributions to environmental research.

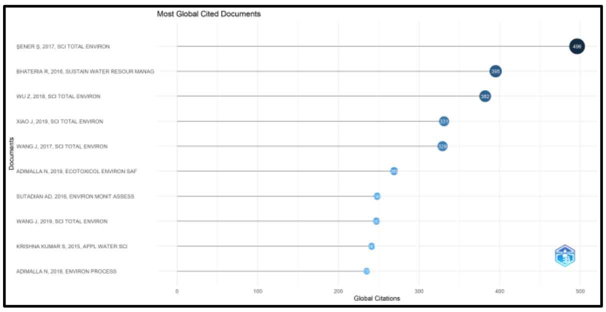

Fig. 5. Most Relevant Documents.

5 Challenges and solutions

When applying Water Quality Indexes (WQIs) in real-world situations, several challenges can arise. These challenges include the selection of appropriate parameters for the index, as many factors such as biological, chemical, and physical parameters must be considered to accurately assess water quality. Furthermore, the variability in water quality over time and across different geographical regions can complicate the application of a uniform WQI. Additionally, the availability and reliability of data pose significant challenges, as incomplete or inaccurate data can lead to misleading WQI results. Another major challenge is the interpretation of WQI scores, as these scores need to be understood and used by policymakers, water managers, and the public effectively.

To overcome these challenges, several solutions and recommendations can be adopted. Firstly, it is essential to tailor the selection of parameters in the WQI to the specific water body being assessed, taking into account its unique characteristics and the primary concerns related to its use. Developing regional or site-specific WQIs can also help address the variability in water quality. To tackle the issue of data availability, efforts should be made to improve water quality monitoring networks and data sharing practices. The use of modern technologies such as remote sensing and data analytics can enhance data collection and accuracy. Moreover, clear guidelines and training on interpreting and using WQI scores should be provided to ensure that the results are effectively communicated and utilized in decision-making processes.

6 Conclusion

In conclusion, our bibliometric exploration of publications on Water Quality Indices (WQI) reveals a dynamic and diverse research landscape. Institutions such as Chang'an University and journals such as "Water (Switzerland)" stand out for their prolific contribution to the scientific literature in this field. Authors such as Zhang Y. dominate in terms of number of publications, reflecting the vitality of individual research efforts.

The most cited papers, notably those published in "Science of the Total Environment", underline the impact and relevance of the studies carried out. These influential works, widely recognized by the scientific community, reflect significant advances in the understanding and application of WQI to assess the quality of water, a vital resource.

This bibliometric synthesis, while not exhaustive, provides an illuminating overview of current trends and key players in WQI research. It highlights the importance of international collaboration and multidisciplinarity in environmental studies. Ultimately, it confirms that water quality remains a major issue for researchers and decision-makers worldwide, motivating further in-depth and innovative research in this crucial field.

Water Quality Indexes (WQIs) stand as a cornerstone in the realm of water management, offering a critical tool for the synthesis and interpretation of complex water quality data. By condensing a wide range of water quality parameters into a singular, comprehensible score, WQIs facilitate a nuanced understanding of water health that is accessible not only to scientists and environmental managers but also to policymakers and the general public. This simplicity and clarity in communication are indispensable for effective decision-making, enabling stakeholders to identify and address water quality issues promptly and efficiently. In essence, WQIs serve as a bridge between detailed scientific data and actionable information, empowering informed management and policy decisions that are vital for the conservation and improvement of water resources globally. Their utility in translating intricate environmental data into actionable insights underscores the pivotal role of WQIs in ensuring sustainable water management practices.

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