iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** II **Month of publication:** February 2026

DOI: https://doi.org/10.22214/ijraset.2026.77617

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue II Feb 2026- Available at www.ijraset.com

Water Quality Indices (WQI) with Special Reference to CCME-WQI: Evolution, Methodological Framework, and Applications in Riverine Systems

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Abstract: Assessment of water quality is essential for safeguarding human health, sustaining aquatic ecosystems, and supporting effective water resource management. Owing to the multidimensional nature of water quality datasets, Water Quality Indices (WQIs) have emerged as practical tools for integrating complex physicochemical information into a single, interpretable metric. This mini review synthesises the conceptual evolution, structural framework, and methodological components of WQI models, with particular emphasis on parameter selection, sub-indexing, weighting schemes, and aggregation functions. Special attention is given to the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), highlighting its statistical foundation, flexibility, and widespread applicability in riverine environments. The review summarises global applications of CCME-WQI across diverse hydro-climatic and pollution contexts, demonstrating its effectiveness in detecting spatial variability, pollution gradients, and deviations from water quality objectives. Key limitations of conventional WQI approaches, including subjectivity and eclipsing effects, are also discussed. Finally, future research directions are outlined, emphasising the integration of biological indicators, land-use drivers, and data-driven techniques to enhance the ecological relevance of WQI-based assessments. Therefore, this review emphasizes the continued relevance of CCME-WQI as a robust decision-support tool for river water quality assessment and sustainable river basin management.
Keywords: Water, CCME-WQI, Pollution, River, Assessment.

I. INTRODUCTION

Water quality assessment is fundamental for ensuring the safety of water resources used for drinking, irrigation, recreation, and sustaining aquatic ecosystems. Rivers, in particular, support complex ecological processes and biodiversity, making their continuous monitoring crucial for effective water resource management. Reliable and interpretable surface water quality information is therefore essential for policy formulation, conservation planning, and sustainable management [1], [2], [3].

Given the multidimensional nature of water quality datasets, the use of Water Quality Indices (WQIs) has emerged as an effective approach to condense complex physicochemical information into a single numerical value that is easily interpretable by scientists, managers, and policymakers. A WQI integrates multiple water quality parameters into an index score, enabling rapid assessment of water status and facilitating communication with non-technical stakeholders [4], [3]. This mini-review aims to synthesise the conceptual evolution, methodological framework, and practical applications of Water Quality Indices, with particular emphasis on the CCME-WQI, to highlight their relevance and utility in riverine water quality assessment.

II. EVOLUTION OF WATER QUALITY INDICES

The conceptual foundation of WQIs emerged shortly after the formal recognition of “water quality” as a measurable environmental attribute. Horton’s pioneering work introduced a mathematical framework that combined multiple water quality variables into a single index score, marking a paradigm shift in water quality evaluation [5]. This approach strongly influenced subsequent WQI development. Later, Brown and colleagues, in collaboration with the National Sanitation Foundation, developed the widely adopted NSF-WQI, refining Horton’s methodology with improved parameter selection and weighting. With increasing demand for water quality evaluation across diverse usage scenarios, more flexible indices were introduced. A significant milestone was the formal recognition of the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) in 2001, evolved from the earlier British Columbia Water Quality Index [6].

Recent decades have witnessed methodological advancements through the incorporation of multivariate statistics, soft computing techniques, machine learning, and artificial intelligence for parameter optimization and index formulation [7], [1], [8]. To date, more than 35 WQIs have been developed worldwide, reflecting regional priorities, data availability, and intended applications [5], [9].

III. STRUCTURAL FRAMEWORK OF WQI MODELS

Despite their diversity, most WQI models follow a common four-step framework:

1) Selection of water quality parameters,
2) Transformation of parameters into unitless sub-indices,
3) Assignment of weights based on parameter importance, and
4) Aggregation of weighted sub-indices into a final index score, followed by classification into quality grades [5], [10].

IV. PARAMETER SELECTION, SUB-INDEXING, WEIGHTING, AND AGGREGATION

Most of the time, WQI model parameters were selected according to the availability of data, expert opinion, or the importance of a water quality parameter to the environment [9]. Many studies altered the model parameter lists depending on the accessibility of the data. Because of this, it is sometimes not possible to add some most important water quality parameter into an WQI [11]. There are no standard criteria or recommendations for choosing the water quality parameter to be included in the WQI model. It appears that a few typical water quality concerns, such as availability of oxygen, eutrophication state, health hazards, and dissolved components, were taken into consideration while selecting the WQI model parameters [9].

The basic objective of the sub-indexing is to transform parameter concentrations into unitless values called parameter sub-indices. The CCME index and the Dojildo index skipped this step and used the parameter concentrations instead of sub-indices to execute the final aggregation function [5], [9].

The parameter weight value is often computed based on the relative relevance of the water quality parameter and/or the proper water quality guidelines [9]. Most WQI models used techniques called "unequal weighting," in which the sum of all the parameter weights was 1. The CCME index, the Dojildo index, and the Smith index models estimate the final score without employing the weight values [9]. The process of aggregation is the final phase in the WQI model. It is used to combine the parameter sub-indices into one water quality index score [12].

V. SIGNIFICANCE OF WQI

WQI synthesises complicated scientific data in a manner that makes it is readily comprehensible to the general public. As a result, a WQI based on several essential water quality parameters may be identified as a basic indicator of water quality that offers a broad concept about potential water resource challenges [5], [6]. WQI might be beneficial for analysing the spatial as well as temporal variations in water quality data. This allows managers to identify pollution hotspots, seasonal degradation patterns, and long-term trends in river health. WQI is also useful for informing the general public about the water quality status of certain water resources [13], [14]. WQIs are incredibly useful in scientific study for evaluating the effectiveness of any eco-restoration, rejuvenation, or water treatment program, as well as for assessing river health. Furthermore, it may be advantageous to assess the influence of any pre- and post-developmental activities on riverine health [13].

VI. LIMITATIONS OF WQI

The use of WQI frequently has time and space limitations. The grading of river water quality using the WQI technique is likewise a contentious issue among academics, scientists, and water quality managers. Without addressing some other Water quality parameters, a single number including a subset of water quality parameters cannot convey the whole information of about the water quality. Due to its reliance on the opinions of experts, WQI might have ambiguity and subjectivity issues. Eclipsing and ambiguity are two main drawbacks of the WQI tools [6]. Eclipsing occurs when poor quality in one parameter is masked by acceptable values of others, potentially leading to misleading index scores.

VII. GLOBAL APPLICATIONS OF CCME -WQI IN RIVER HEALTH ASSESSMENT

At the beginning of the twenty-first century, the CCME-WQI was developed from the earlier British Columbia Water Quality Index (BCWQI) model [6], [7]. The CCME-WQI framework requires a minimum of four water quality variables for index computation [9]. It integrates three statistical components: scope, frequency, and amplitude to quantify the extent, consistency, and magnitude of deviations from water quality objectives [15].

Applications of the CCME-WQI span a wide range of riverine systems across different hydro-climatic and pollution contexts. In Bangladesh, Munna *et al.* assessed the pollution status of the Surma River using the CCME-WQI framework and classified the river water as being in poor condition, indicating persistent anthropogenic pressure and reduced suitability for domestic use [16]. In North Africa, Hamlat *et al.* evaluated the Tafna River basin in Algeria using multiple water quality indices and demonstrated that CCME-WQI was particularly effective in diagnosing the overall drinking water quality status, owing to its integrative treatment of guideline exceedances across parameters [17].

Similarly, Abdel-Satar *et al.* applied CCME-WQI to appraise the Nile River and revealed pronounced spatial variation in water quality suitability for drinking and aquatic life, highlighting the sensitivity of the index to pollution gradients along large river systems [18]. In Turkey, Bilgin assessed the Coruh River basin using CCME-WQI and showed that the index provided reliable detection of surface water contamination, supporting its applicability in mountainous and high-energy river environments [19].

In the Indian context, CCME-WQI has been widely applied to evaluate river water quality under intense anthropogenic stress. Sharma and Kansal applied the index to the Yamuna River and identified substantial deterioration in water quality associated with urban and industrial inputs [20]. Haldar *et al.* similarly assessed the Damodar River and demonstrated the effectiveness of CCME-WQI in capturing spatial variability in industrially impacted river systems [21]. More recently, CCME-WQI was applied to the Mundeswari River, where pronounced spatial differences in water quality were observed, further confirming the utility of the index for river health assessment in tropical rivers subjected to cumulative human pressures [3].

VIII. CONCLUSIONS

Water Quality Indices have emerged as indispensable tools for synthesising complex water quality datasets into interpretable metrics that support river health assessment and environmental decision-making. Among the various indices developed globally, the CCME-WQI stands out due to its methodological simplicity, flexibility in parameter selection, and robust statistical foundation. Its widespread application across diverse hydrological, geographical, and pollution contexts demonstrates its reliability for assessing spatial variability and overall river water quality status. However, conventional WQI approaches remain limited by subjectivity, parameter eclipsing, and the exclusion of biological and landscape-level information. Future research should therefore focus on integrating biological indicators, land-use drivers, and advanced data-driven techniques to enhance the ecological relevance and management utility of WQI-based assessments, particularly in increasingly stressed riverine systems.

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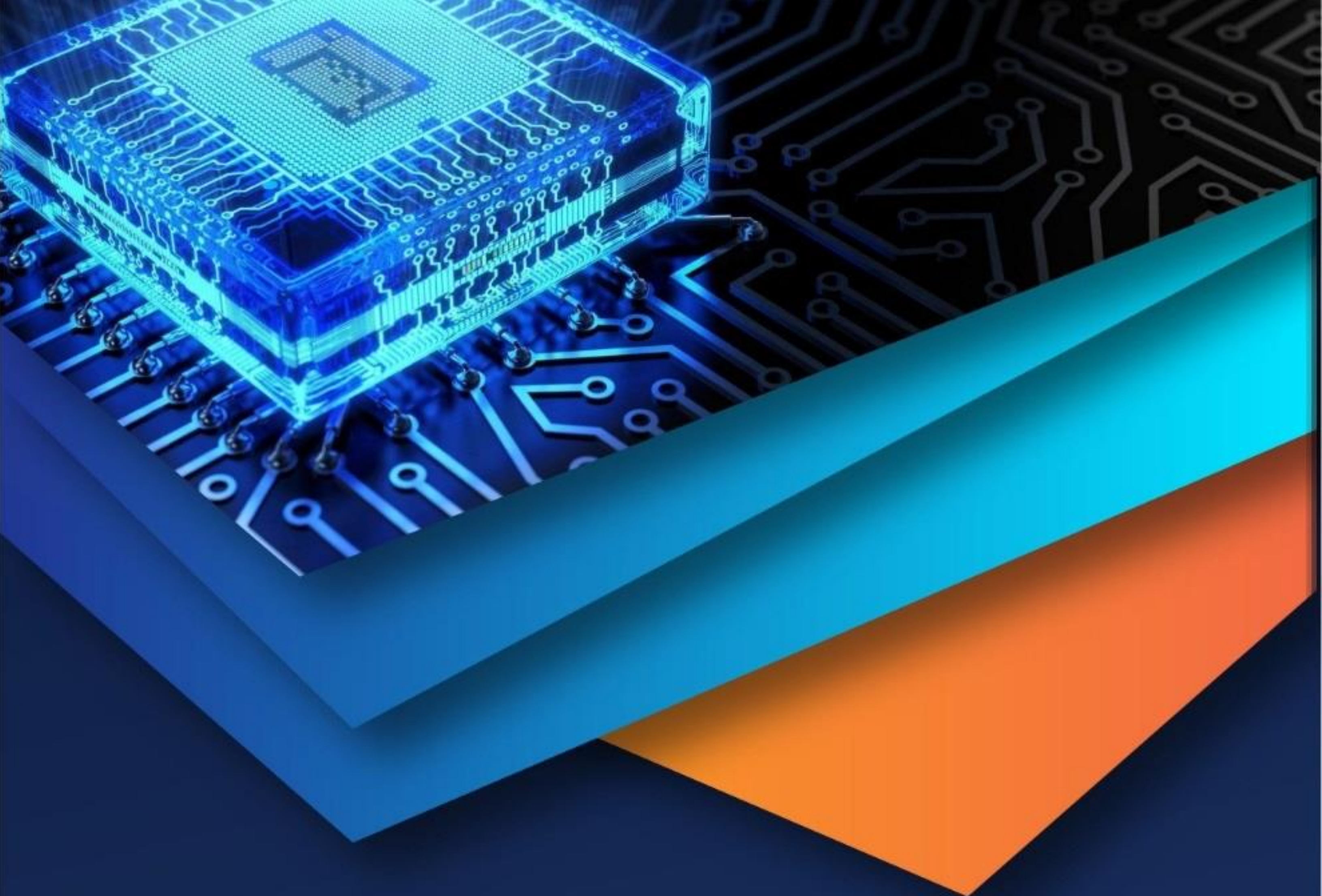

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