



WATER QUALITY IN DRINKING WATER DISTRIBUTION SYSTEMS: A WHOLE-SYSTEM APPROACH TO DECISION MAKING

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Abstract

Water utilities are responsible for continuously providing safe water to consumers through their drinking water distribution systems. Avoiding siloed approaches that may lengthen critical response times in the case of a water quality hazard can be accomplished through a whole-system approach. To achieve this objective, providers need to pursue the state-of-the-art knowledge and techniques across all facets of water quality management as our understanding of these complex infrastructures continually evolves.

This study provides a comprehensive and up-to-date bibliometric study of water quality in drinking water distribution systems over the first twenty years of the 21st century. Analysis of the relevant literature reveals how the research landscape has expanded in terms of number of publications made, variety of topics, and geographic diversity. Each region has a unique 'research identity' in the different topics focused upon, yet the presented inter-dependency of factors impacting water quality emphasises the opportunities for sharing of best practices.

Keywords

Water quality, distribution systems, decision support, water utilities, bibliometric study, drinking water management

1 INTRODUCTION

Drinking Water Distribution Systems (DWDS) can interact with the water they transmit, affecting the quality of water received by consumers. Some of the spatial-temporal variability measured in typical water quality parameters can be predicted and explained by known factors, such as those related to increased temperatures [1,2], planned operations and maintenance [3,4], and distribution materials and configuration [5,6]. However, random unforeseen events can drive potentially rapid deterioration of water quality, including microbiological and chemical concerns. Utilities have an obligation to intervene and manage such risks, but siloed and reactive approaches can lengthen response times. This could lead to events that may expose the population to regulated and non-regulated contaminants in drinking water, and ultimately public dissatisfaction and increased repercussive costs.

Managing the vast infrastructures of DWDS is a complex challenge, and providers continually pursue the state-of-the-art knowledge and techniques to maintain and elevate water quality beyond regulation compliance. Extensive research and the accrued experience of system operators built over many decades tackle how different facets of water quality behave individually and interact together within the system [7]. Diverse approaches have contributed new pieces of knowledge and practice to the wide field of DWDS water quality; however, our understanding is not complete and necessitates constant evolution. To effectively manage water quality events now and into the future, drinking water managers require a whole-system approach to water quality that can instigate the adoption of preventative and curative actions.

Bibliometric studies are the quantitative analysis of literature within a subject to understand the major concepts and temporal and geographical patterns within sub-disciplines. From these studies, researchers and practitioners can identify the present status, topic hotspots and gaps, and form a consensus across the relevant literature, which may change over time. Few papers have previously performed bibliometric analysis within the field of water quality in DWDS; yet they have focused exclusively on a particular topic, such as disinfection by-products [8] and disinfectant residual stability [9], or location, such as drinking water research in Africa [10]. A bibliometric study conducted from 1992 to 2011 by Fu, Wang and Ho [11] outlined a more holistic overview across multiple topics relevant to water quality in DWDS. Yet, the rapidly changing pace and diversity of drinking water research means that this study needs to be updated as it is now out of date and potentially limited when extrapolating to future challenges.

This study aims to gain an integrated understanding of the events and factors that impact water quality in DWDS. A comprehensive and up to date bibliometric study at the macro-level is presented, detailing the global research landscape and how it has evolved over the first twenty years of the 21st century. We will highlight the main trends in water quality research and explore the most consistently prioritised areas of research.

2 APPROACH

2.1 Sourcing Literature

Potential literature was sourced from the well-known and established SCOPUS database; chosen as SCOPUS has a wider journal base than its other citation databases [12]. Records published in English between 2000 and 2020 were searched using the keywords “water quality distribution system”. The vast range of topics relating to this field and the variety of terminology deployed (e.g., “water distribution network”, “drinking water distribution system”, “piped water network”), meant that a narrower scope could not be used. Duplicates, retracted articles, and anonymous records were dismissed through a preliminary screening. Therefore, a total of 13,019 records were exported.

Three eligibility criteria were applied to filter records relevant to the aim of the study. Firstly, it was required that the literature primarily focus on knowledge and/or management of water quality in DWDS between the treatment works and the customer boundary. Secondly, only continuously pressurised systems with surface or groundwater sources were considered. Studies relating to intermittent water supply, reclaimed water, or ultrapure water were not included in this review. Thirdly, epidemiological studies were deemed to be outside the scope of this study.

Potential records were carefully manually evaluated against the eligibility criteria using the title, keywords and abstract. Where there was ambiguity, the full publication was retrieved to enable further examination. Any records that did not meet the requirements were removed, leaving 1868 eligible literature sources. Of these, 91% were available to be downloaded as full publications. Identifying information for the 1868 individual sources were compiled into an Excel spreadsheet for bibliometric analysis, such as title, author names, year of publication, document type (e.g., journal paper, conference paper, report, book chapter), source, and digital object identifier (DOI).

2.2 Classifying Literature

To determine the research landscape, each publication was classified into a theme that described the study’s main area and ‘tagged’ with up to three different topics within that overarching theme. As an example, a paper titled “Do Transients Contribute to Turbidity Failures of Water Distribution Systems” [13] was classified within the *Hydraulic Behaviour* theme and tagged with the *Dynamic Hydraulics*, *Particle Mobilisation*, and *Discolouration* topics based on the content of

the paper. Nine themes and 47 topics were conceptualised. These themes and example topics are: 1) infrastructure – corrosion, pipe material, leaching; 2) chemicals & treatment decay – chlorine, disinfection by-products, metals; 3) contamination – intrusion, backflow; 4) hydraulic behaviour – stagnation, dynamic hydraulics, pressure; 5) microbiology – biofilm, coliforms, fungi; 6) water aesthetic – discolouration, particles, taste and odour; 7) utility management – flushing, utility management, regulation compliance; 8) technology – sensors, monitoring, simulations; and 9) external factors – temperature, treatment implications, social aspects.

3 RESULTS

3.1 Temporal Changes in Publications

A database of 1868 publications relating to water quality in DWDS were found to be published between 2000 and 2020. Two-thirds of the literature were journal papers (1231), 31% were conference papers (579), and the remaining sources (58) consisted of books, magazine articles, and technical reports. Figure 1 shows how the publication rate varied considerably from average of 89 publications per year. The lowest number of publications (40) occurred in 2002, where the highest number of publications (129) occurred in 2018. Overall, there was a significant positive increase in relevant publications over the two decades (Pearson coefficient 0.75).

In the majority of the years investigated, more journal papers relevant to this study were found than conference papers. The only exception was in 2006 when 66 conference papers were determined to be eligible, compared to 41 journal papers. This finding aligns with a burst of conference papers published between 2005 and 2010, most likely due to an alignment of several major conference series: World Environmental and Water Congress, Water Distribution Systems Analysis Conference, Computing and Control in the Water Industry Conference, Water Quality and Technology Conference and AWWA Annual Conference and Exposition.

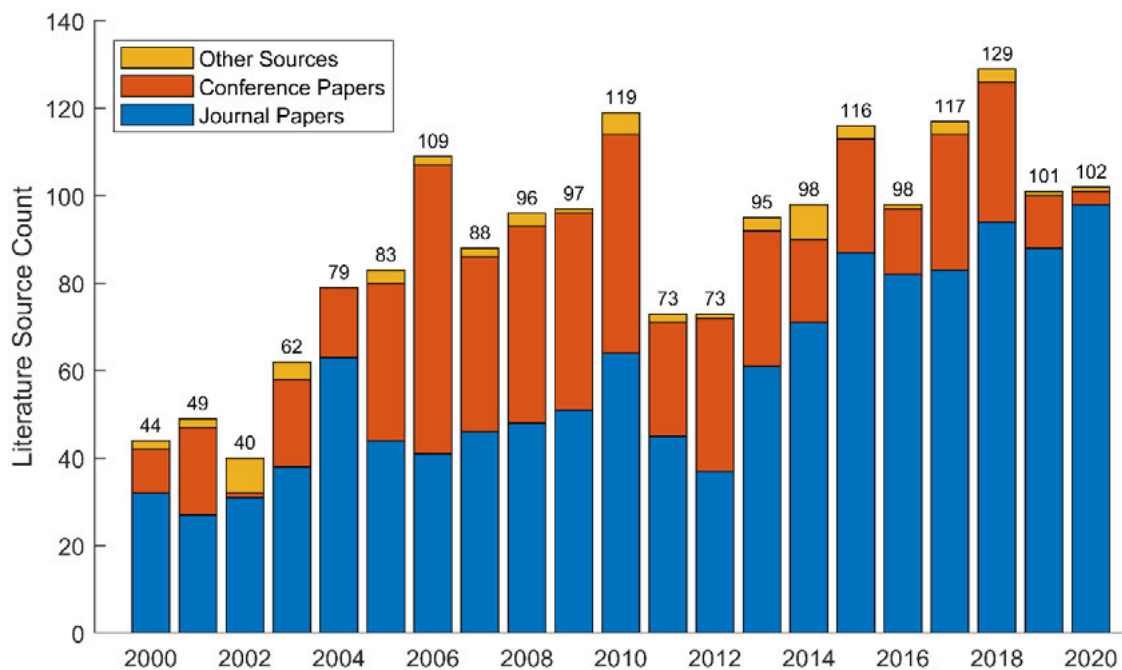


Figure 1. Eligible literature published per year between 2000 and 2020.

3.2 Geographical Changes in Publications

Of the 1868 publications investigated in this study, three quarters (1391) referenced a study location at the community, region or national scale. It is important to note this is not where the authors' associated institution is based, but rather where the research was performed or situated. A total of 58 countries were represented across North American, South America, Europe, Africa, Middle East, Asia, and Oceania. Figure 2 presents the number of studies published per year for each of these regions.

Half of the total literature (970) was based in North America and Europe, predominantly the United States of America, Canada, the UK, the Netherlands, and France. The research dominance of these countries in terms of productivity is well recognised across most scientific fields [14]. Studies centring in North America peaked in 2005-2006. It appears that this research peak corresponds to a surge of literature focusing on contamination and monitoring technologies that is most likely in reaction to the "9/11" terrorist attack in New York City. This catastrophic event brought to the research forefront DWDS' vulnerability against deliberate threats. Over the two decades, literature based in Europe was published at an increasing rate (Pearson coefficient 0.84) with a growing number of studies in the later years based in Central and Eastern European countries, such as Romania and Poland.

All seven regions were mentioned in the literature for the first time in 2009 and for seven of the following years, which suggests a turning point in the diversity of water quality research in DWDS. Studies based in Africa, the Middle East, and South America have grown in number, but these regions still remain a small share of the total field (109, 5.8%). In contrast, literature representing Asian DWDS has rapidly increased (Pearson coefficient 0.91). Accelerated rates of publishing from China, India, and South Korea in particular mean that, in the last five years investigated (2016-2020), there are more studies investigating water quality in DWDS in Asia than in North America.

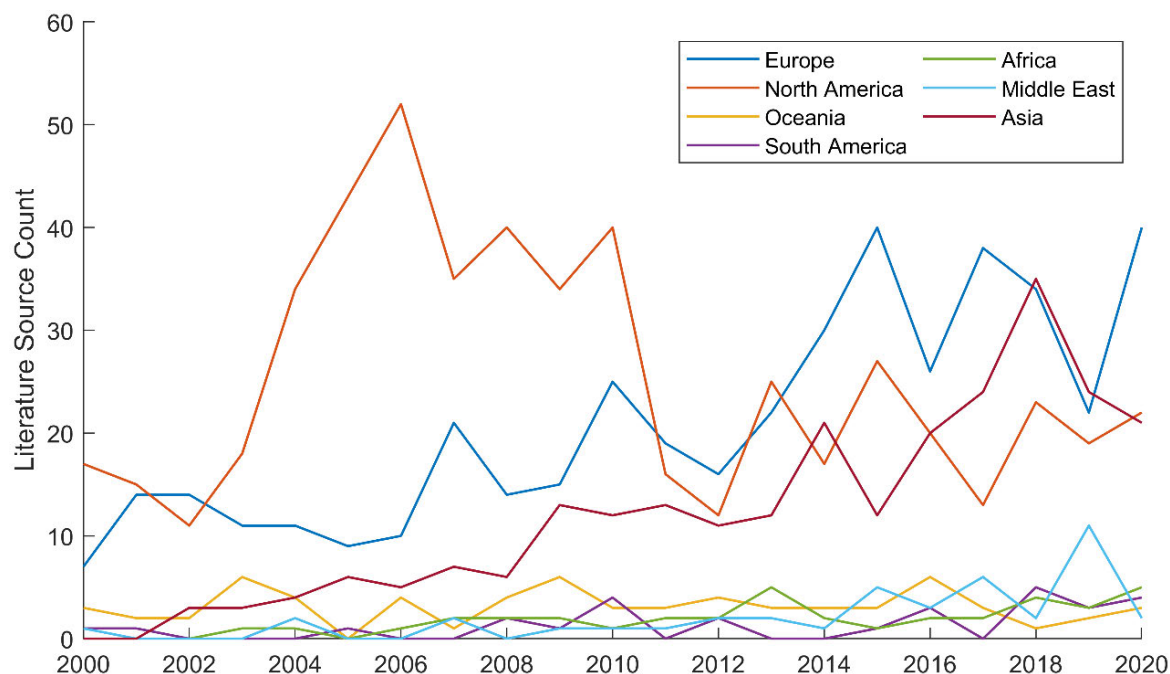


Figure 2. Study locations represented by the literature categorised into regions.

3.3 Research Themes

The most popular themes and the corresponding number of literature sources were technology (528), chemicals and treatment decay (362), and microbiology (337). Given the exponential advances made since 2000, it was unsurprising that technology was the most common theme. Significantly greater data storage and processing power mean complex simulations have become normalised, aided by cheaper and more accessible devices to measure water quality. The chemicals and treatment decay theme (referring to research involving chemical reactions or decay of chemicals added during water treatment) has experienced the greatest expansion in terms of publications per year (Pearson coefficient 0.76). Less prevalent themes of infrastructure, contamination, hydraulic behaviour, water aesthetic, utility management, and external factors remained stable over the two decades investigated. Overall, these less prevalent themes averaged five publications per year, where technology, chemicals and treatment decay, and microbiology averaged 25, 17, and 16 publications per year, respectively.

Each geographical region has a unique profile of themes studied relative to the total number of publications associated in those countries, which is represented in Figure 3. These ‘research identities’ exist as a product of multiple factors, such as national/regional priorities, personal interests of researchers, funding opportunities, and environmental contexts.

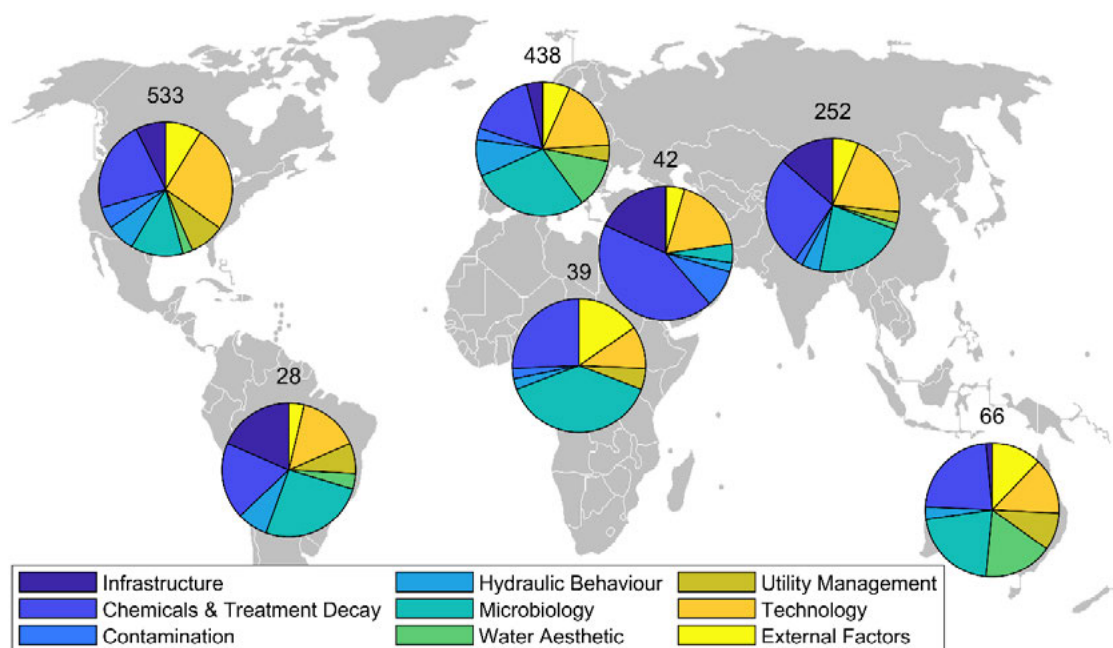


Figure 3. Geographical representation of the different themes. The total number of publications over the study period is presented for each region.

3.4 Research Topics

Each literature source was ‘tagged’ with up to three different topics that aimed to capture the work’s focus. Three-quarters of publications (1412) were assigned three topics, 425 publications were assigned two topics, and 31 publications were assigned the minimum of a single topic. The ‘top five’ topics and their respective frequencies of use were simulations (647), chlorine (369), biofilm (368), intrusion (327), and monitoring (310). In contrast, the ‘bottom five’ topics were backflow (4), pipe maintenance (4), pumps (12), parasites (12), and fungi (13).

To determine if topics occurred in frequent combination, the topics were coded into pairs, e.g., transient-intrusion, chlorine-water age, metals-discolouration. When the order of the topics assigned to the publication was ignored, a total of 617 unique pairs were found, out of a possible 1081 pairs using 47 different topics. The most popular topic pairs and their respective frequencies were simulations-chlorine (177), simulations-intrusion (169), monitoring-intrusion (144), simulations-monitoring (131), and simulations-velocity (86).

Figure 4 visually depicts the pairings found in this study where line thickness indicates how frequently the respective pair was found in the literature. Only pairs that occurred at least five times are included, and the colours are simply for visual clarity. This figure visually accentuates the breath and interconnectivity of topics relating to water quality in DWDS.

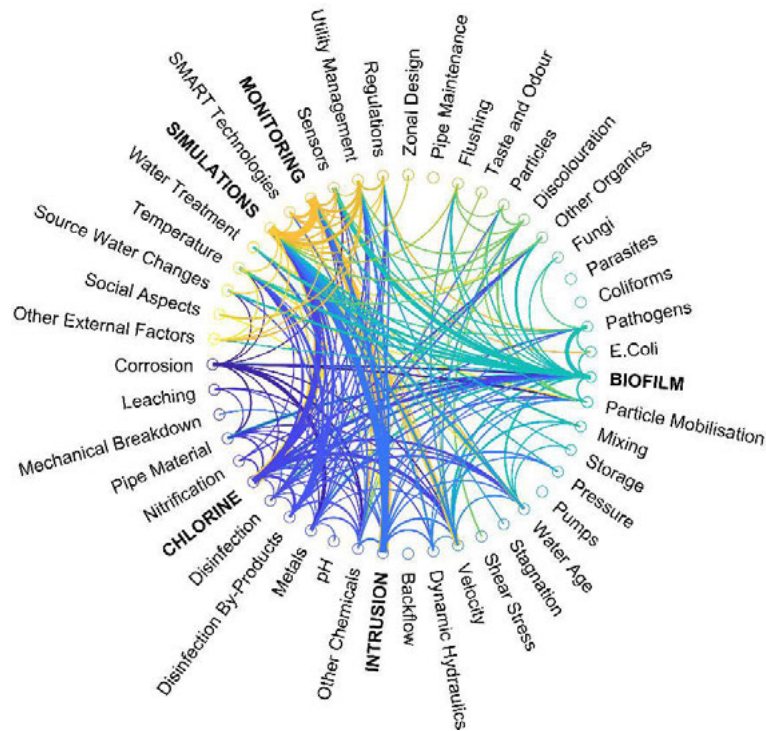


Figure 4. Illustration of the topic pairs observed in the literature. The five most prevalent topics are highlighted in bold font.

4 CONCLUDING REMARKS

This study presents an up-to-date overview of research published between 2000 and 2020 that examines water quality in drinking water distribution systems. The findings show how this field has expanded over the two decades in terms of number of publications made, variety of topics, and geographic diversity that represents the increased research capacity of countries in the Global South. Relevant research is now being performed around the globe that reflects the universal need for safe drinking water. Topic analysis has indicated that intrusion, chlorine, biofilm and monitoring are currently prevalent disciplines of research, enabled by increasingly advanced simulations and technologies. This study has exhibited the inter-dependency of factors impacting water quality, yet also highlighted how different focuses are unique to each region. It is important to acknowledge these changing priorities and perspectives, and the opportunities they provide for cross-border thinking and sharing of best practice.

This work forms the first stage of a larger project to develop an integrated decision support system that consolidates scientific knowledge on the spatial and temporal variability of water quality with recommendations from government entities and best practices for municipal management. The literature database developed will serve as an expert knowledge base for the decision support system, which will be incorporated into WaterShed Monitoring's data storage and management software Enki®.

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