Article

Water Sustainability in the Context of Global Warming: A Bibliometric Analysis

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Abstract: Sustainable water use is becoming a key problem in the present time, since global warming is having a strong impact on usable water resources. This study aims to provide a systematic bibliometric analysis on water sustainability in the context of global warming, in order to provide a clearer view on the existing research trends and to find eventual gaps in research that can be exploited in the future. The selection and analysis of the most relevant papers discussing the chosen topic pointed out a strong increase in research in the last period, dominated by US scientists and research entities, with researchers focusing on either the present impact of global warming on water sustainability and its effects on water supply and ecosystem functioning, or on problem solving and creating a framework for water sustainability in the context of global warming, or on the future perspectives and potential solutions for achieving water sustainability in the future period. The study pointed out that only 6% of the article regarding water sustainability include information about global warming, with an increasing trend in the latter period in both the number of articles and citations, but the field of study seems to be incipient, with a large number of journals publishing a very low number of articles. The main drawbacks identified were the orientation of a large majority of the studies on present day problems and not on future approaches, the complete lack of studies regarding the role of preserving natural habitats or of spontaneous renaturalization, as well as the relative absence of including cultural aspects in addressing water-sustainability issues.

Keywords: water management; sustainability; global warming

1. Introduction

Since the Brundtland Commission published its seminal report “Our Common Future” [1], “sustainable development” and “sustainability” have become basic ideas in policy generation, state and regional administration and scientific research; development and the environment are considered a single issue, and our new common goal became “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, leading Mays [2] to define “water sustainability” as the ability to use water resources in quantity and quality suitable for both the present and future needs of human populations and ecosystems, in such a way that we can protect human populations from the effects of natural or man-made hazards. Mays also pointed out that, among other factors to be considered, the change in climatic conditions, at both regional and global levels, plays a crucial role in achieving the goal of sustainable water use [2] as well as the role of the regional management of water resources versus a more decentralized approach [3]. In this context, an analysis of the water-sustainability aspects in relation to global warming presented in the scientific literature might point out the existing research trends in the field, as well as conceptual gaps, leading to the identification of potential future analysis that could improve the scientific knowledge and provide useful tools for addressing water-sustainability cases, at both regional and local levels.
Although the present–future binomial concept was clearly defined and its mechanisms were theoretically viable, practical water policies and uses are far from ideal, especially in areas affected by water scarcity and with developing socio-political regimes, as pointed out by Wada and Bierkens [4], who presented consistent information about the worldwide overuse of aquatic resources, with notable examples from the Aral Sea [5], Colorado and the Yellow River [6], Northwest India and Northeast Pakistan [7,8], and the Tigris–Euphrates system [9], etc. Some of these examples are strictly man-made hazards, such as the case of the Aral Sea, but in most situations, we can identify the influence of global climatic changes as a consistent factor in the degradation of aquatic ecosystems worldwide.

The complex problematics of sustainable water-resource management in the context of global climatic changes also encompasses aspects regarding the dependence of agricultural production on unsustainable groundwater [7,10,11], non-sustainable industrial use [12,13] or the operation of mining facilities [14].

At the current point, two main ideas have emerged from the scientific community. On one hand, water consumption will increase accompanied by an increase in the number of areas and hydrographic basins affected by water-scarcity problems [15–18], leading to the necessity of a more complex approach in managing water resources at both local and regional scales. Therefore, MacDonald [19] argued that “21st-century sustainability challenges in the Southwest will also require planning, cooperation, and integration that surpass 20th-century efforts in terms of geographic scope, jurisdictional breadth, multisectoral engagement, and the length of planning timelines”, an opinion supported and supplemented by Gleick [17], who included, as a key factor in water-resource-management planning, the human factor in all its aspects: cultural, demographic and educational.

On the other hand, a socio-anthropological current is currently investigating aspects regarding sustainable water management, starting from the concept developed by Mauss [19], of treating water as a “total social fact”. The ideas resulting from this approach are centered on the role of human perception of water [20,21], defined as “not only as a resource, but also as a substance that connects many realms of social life” [22]. Sivapalan et al. coined the term socio-hydrology [23], a scientific field focusing on “understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle at multiple scales, with explicit inclusion of the two-way feedbacks between human and water systems”, a concept that poses human society and water in interdependence and provides tools for a future cultural basis of water-resource conservation. However, this anthropological approach has the drawback of excluding global warming from the equation and mostly relying on small-scale models.

Starting from these premises, our objectives are (1) to provide a comprehensive analysis of the literature referring to the relations between water sustainability and global warming, (2) to identify the main research trends and their temporal evolutions, and (3) to point out the directions and the intensity of the collaborations between individual researchers and research entities. Our analysis consisted of three successive phases: a literature selection phase, in which we used a set of criteria to create a list of relevant documents related to the research field; a descriptive analysis of the selected papers, where we provided relevant information regarding the temporal evolution of the scientific interest and pointed out the main providers of scientific literature in the selected field; and a bibliometric analysis, which explained the main research trends and the relations between researchers and research entities. The article is composed of six sections: introduction; a section detailing the review methodology; a section containing the descriptive statistics of the articles selected after the data-collection phase; a section presenting and explaining the results of the bibliometric analysis; and, finally, a discussion section, where we presented our findings, we identified potential gaps in the research and proposed future research directions.
2. Materials and Methods
The literature analysis was conducted in the framework of the PRISMA-S system, consisting of six successive phases:

- Identification of scientific manuscripts.
- Screening of the identified manuscript for compliance with the general scope of the review.
- Filtering of the manuscripts referring to the specific goal of the review, by including only manuscripts referring to water sustainability in relation to global warming.

The selected papers were included in a two-phase analysis:

- A descriptive analysis, pointing out a) the temporal trends in research in the analyzed field and b) the main contributions of authors, countries, scientific journals, and research centers.
- A bibliometric analysis, pointing out (a) the main research directions and trends in the analyzed field and (b) the collaborations between authors and countries involved in research in the analyzed field.

2.1. Data Collection

The search was conducted using the Web of Science database, considered as containing the most significant scientific results at the present moment. The search included the entire time frame of the database, from 1975 to 2022. We focused on papers containing the terms “water” and “sustainability”, and “global warming”, mainly in the title and keywords. The search resulted in 3995 scientific manuscripts. Two duplicate records were found and eliminated from the list, resulting in a preliminary list of 3993 manuscripts.

2.2. Screening Process

The first phase of screening was the exclusion of the papers referring only to water sustainability and not considering aspects of global warming. Out of the 3993 papers, only 206 were found to refer to water sustainability aspects strictly in the context of global warming; the rest of the papers referred to aspects regarding water sustainability without considering climate change. The exclusion of the non-suitable papers was carried out by reading their abstracts and keywords by both the researchers and the elimination of the papers was consensual. One paper was written in German and was also excluded, leaving a list of 205 papers.

Only peer-reviewed papers were included in the analysis, as a second phase of screening, book chapters, editorial materials, and conference papers were excluded. In addition, we excluded reviews from the selection, including only manuscripts classified as “article” in our analysis. The second phase of screening identified 35 manuscripts belonging to the excluded categories; therefore, the post-screening list consisted of 170 articles.

2.3. Eligibility Assessment

We used two criteria for the selection of relevant papers: (a) by re-reading their abstracts and eliminating the articles beyond the study’s scope, and (b) examination of the articles by reading the full texts. For both phases, the two researchers independently read the abstracts and the full text of the papers, respectively, and consensually eliminated the papers not suitable for inclusion in the review. Six articles were eliminated after reading the abstracts, which clearly showed the aspects presented did not fall into the objective of our study, while another 27 were eliminated after reading their full text.

We eliminated papers referring to educational aspects (frameworks for training specialists or the general public regarding water-sustainability aspects), papers referring to state policy aspects regarding water sustainability and papers referring to the sustainable
use of natural resources that have implications for the water cycle. Figure 1 presents the flowchart of the literature search and the successive aspects of the screening process.

Figure 1. Literature selection process.

2.4. Bibliometric Analysis

For the bibliometric analysis, we used the VOS viewer software which analyzes numerous types of interrelations between manuscripts (bibliographic coupling, co-authorship, co-citation, and co-occurrence of keywords) by linking relevant and similar items, and produces network visualizations of the analysis. The software can use data from several bibliographical databases (e.g., WoS, Scopus, PubMed, RIS, Crossref JSON files), and is freely accessible at: http://www.vosviewer.com (accessed on 2 February 2022).

In our analysis, we looked for two separate aspects:

- Identification of the main research trends in the field of water sustainability in relation to global warming: for this purpose, we applied a text data analysis in which we included the full text of the selected manuscripts, at full counting (the total number of occurrences) in order to identify the most used terms and their connection inside the analyzed documents; the selected terms had at least 15 occurrences, and the list
was cleared of terms usually appearing in scientific literature (e.g., person, year, paper, term, study etc.); we also excluded the term “Arizona”, whose occurrence was in relation with the high number of articles published by researchers from Arizona State University.

- Identification of the relations between the implied researchers and research centers (expressed as countries): for this purpose, we applied two separate analyses: (a) a citation network analysis to point out the most cited researchers and the intensity of the relations between them, and (b) a bibliographical coupling analysis (the situation when two documents cite one or more documents in common [24], identifying the most cited countries in the field of water sustainability in relation to global warming and the intensity of the citation process.

3. Descriptive Analysis

This section provides an overview of the articles studying the relation between water-sustainability and global-warming problematics. We considered three different perspectives for this purpose.

3.1. Temporal Trends of Publication and Citation

The assessed 137 articles produced a total number of 3014 citations, of which there were 2975 without self-citations (98.71%), representing an average of 22 citations per article and corresponding to an H-index of 27. The five top-cited papers (responsible for generating 1053 citations, 34.94% of the total number of citations) and their findings are presented in Table 1.

| Authors                  | Publication Year/Journal Name/No. of Citations                                | Results                                                                 |
|--------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Cayan et al. [16]        | 2010/Proceedings of the National Academy of Sciences of the United States of America/450 | Prediction of the future models of water depletion in the context of increased water consumption. |
| MacDonald [17]           | 2010/Proceedings of the National Academy of Sciences of the United States of America/247 | A model of increased dryness and a framework for reducing unsustainable water consumption.          |
| Davies and Simonovic [25]| 2010/Advances in Water Resources/136                                        | A global water resources model including aspects of the social–economic–environmental system.        |
| Barnett and Pierce [18]  | 2009/Proceedings of the National Academy of Sciences of the United States of America/111 | A model of resource depletion in the Colorado River Basin.                                                        |
| Gleick [15]              | 2010/Proceedings of the National Academy of Sciences of the United States of America/109 | A framework for future water-management practices in the context of new socio-economic challenges.       |

The earliest paper published in the investigated field dates from 2005, and a gradual and stable increase in both publications and citations can be observed from 2009 onward (Figure 2).
The temporal trends of publication and citation were tested, with both parameters showing a significant increase in the last period, indicating a growth in interest in the relations between water sustainability and global warming (Figure 3). Both models show a second-order polynomial ascendent curve, following the equation:

\[ p = 224186.472 - 223.779 \times Y + 0.0558 \times Y^2 \]  

(1)

for the relation between number of articles and time (R = 0.941, p-values of the parameters below 0.05; Y = year, p = number of publications), and

\[ C = 10242497.675 - 10209.799 \times Y + 2.544 \times Y^2 \]  

(2)

for the relation between number of citations and time (R = 0.991, p-values of the parameters below 0.05; Y = year, C = number of citations).

3.2. Distribution of Papers among Research Entities

US authors produced by far the largest number of articles referring to the relation between water sustainability and global change (53 articles producing 1898 citations, of
which there were 1881 without self-citation—99.1%), followed, by a long distance, by authors from China (12 articles with 154 citations), England (12 articles with 210 citations), Canada (11 articles with 110 citations), and Australia (10 articles with 273 citations) (Figure 4). The situation is even better reflected at an institutional level, where the top five research institutions and six out of the first eight are based in the USA (Figure 5), with the largest number of articles coming from relatively dry regions of the US: Arizona (18 articles with 263 citations) [26–28], California (9 articles with 930 citations) [29,30], or Texas (8 articles with 63 citations) [31,32]).

Figure 4. Distribution of articles based on country of provenience.

Figure 5. Distribution of articles based on the research entities involved.

3.3. Distribution of Papers among Journals

The selected articles were published in a very large number of scientific journal (76 journals for 137 articles), with a consistent number (56 journals) publishing a single article
relevant for our study. The top ten scientific journals as far as number of articles are presented in Figure 6, led, in a logical way, by the two journals aiming to publish articles referring to sustainability and water (WATER and Sustainability journals, both with 9 articles published, producing 81 and, respectively, 59 citations). The top ten journals from our list are included by SCImago in the first two quartiles (Q1 and Q2).

A special remark regarding Proceedings of the National Academy of Sciences, whose six published articles constitute for more than one third of the total citations in the investigated field (1025 out of 3014, 34.01%), and provide four of the top five most cited articles [15–18], as well as five of the top ten most cited articles.

Figure 6. Top journals as number of articles published.

4. Bibliometric Analysis

4.1. Analysis of Individual and State-Wise Collaborations

The citation network of the most cited authors studying the relation between water sustainability and global warming shows two clusters of authors with different characteristics (Figure 7). We included in this analysis authors who had published at least two articles in the selected field, reducing the number to 12 authors out of the total 314 authors identified in our study.

The yellow cluster consists of the most prolific authors in the investigated field, Patricia Gober, Kelli Larson and Dave White, researchers from Arizona State University, who each contributed four articles from our list, including a collaboration between two of them or all three [28,33–35]. These authors present a strong link to each other and generate a total number of 194 citation.

The red cluster contains authors with only two contributions, but with a larger number of citations, including authors from the top ten cited papers from our list (for the same number of articles as the authors from the yellow cluster, seven, the authors from the red cluster generated 958 citation).
The bibliographic coupling network (Figure 8) shows three clusters of countries with close collaborations, namely, a blue cluster dominated by US researchers, seconded by collaborators from Italy, South Korea and Turkey (with a total of 67 articles generating 2066 citations); a blue cluster centered around researchers from The Netherlands and Canada, seconded by Iranian, Brazilian and Mexican researchers (with 28 articles generating 730 citations); and a red cluster formed by researchers from eight countries (China, Australia, India, Switzerland, South Africa, Chile, Spain and England), with a fewer individual contributions but with more intense relations between them (with 47 articles generating 521 citations).

4.2. Research Trends in Water Sustainability under a Global-Warming Scenario

The analysis of the most used terms identified a total of 4607 terms appearing in the selected articles, of which only 51 passed the threshold of 15 occurrences established for our analysis, before excluding the terms usually appearing in scientific literature, which resulted in 42 terms remaining. The results revealed three main clusters, indicating the three main research directions in the study of the relations between water sustainability and global warming (Figure 9).
Figure 9. Co-occurrence of key terms—network visualization.

The red cluster is the largest from the representation, comprising 19 terms (almost half of the terms analyzed), of which those with the highest importance are climate change (183 occurrences), water (170 occurrences), impact (136 occurrences), and system (124 occurrences), with lower importance terms such as agriculture (29 occurrences), irrigation (24 occurrences), energy (37 occurrences), drought (39 occurrences), food (17 occurrences) or forest (21 occurrences), indicating that a main research direction is oriented towards the present impact of global warming on water sustainability and its effects on water-supply and ecosystem functioning. We can include here Khan et al.’s analysis of South Korea and India [36], Emami and Koch’s study on Iran’s Boukan Dam [37], de Sa et al.’s study on the Rio Verde Grande basin [38], Fang et al.’s analysis on Chinese lakes [39], Ahmadaali et al.’s assessment of Iran’s Urmia Lake [40] or Yehia et al.’s study on Upper Egypt [41].

The blue cluster (comprising of nine terms) contains the terms sustainability (128 occurrences), management (71 occurrences), approach (55 occurrences), and challenge (51 occurrences), indicating a research trend focused on problem solving and creating a framework for water sustainability in the context of global warming. In this category, we can include Chelleri et al.’s solution for the decentralization of water management in New Mexico [42], Van Leeuwen et al.’s framework for assessing the sustainability of the urban water cycle [43], or Gober and Kirkwood’s dynamic simulation model, WaterSim, applicable to short-term water shortages in urban areas [44].

Finally, the yellow cluster (comprising of 13 terms), containing the terms scenario (115 occurrences), model (117 occurrences), change (108 occurrences), uncertainty (32 occurrences), and, most importantly, future (24 occurrences), seems to define a research trend focused on future perspectives and potential solutions for achieving water sustainability in the future period. For example, Jenerette and Larsen proposed a model of understanding the interactions between urban consumption and the regional availability of renewable water to be used in a future scenario in the event of increased water consumption [45]; Van Leeuwen introduced the concept of City Blueprints, a set of indicators to be
used in the sustainable water management of urban areas [44,46]; Parkinson et al. created a system of trade-offs inside water-energy system configurations for the sustainable management of water flows [47]; while Jacobs et al. proposed a long-term monitoring system for the factors generating drought conditions in Arizona, in order to permit a long-term intervention from state authorities in preventing the effects of water shortage [48].

The temporal overlay (Figure 10) shows a shift in interest from the early studies, from relatively immediate problems (population, drought, city or challenge) to a future-oriented perception, dominated by terms such as future, model, analysis, scenario, management, as well as on the most important effects of a non-sustainable approach to water, represented by the terms food and forest.

![Figure 10. Co-occurrence of key terms—temporal overlay visualization.](image)

5. Discussion and Conclusions

Our study analyzes the problematics of water sustainability in the context of global warming through the use of bibliometrics. Moreover, we tried to identify the eventual gaps in research and proposed a framework for future directions in the field. In this section, we summarize our findings and discuss the challenges in the selected field of research.

For our analysis, we screened a total of 3995 scientific papers and conducted a four-step selection process to identify only research articles specifically examining water sustainability problems in the context of global warming. We observed a significant and constant increase in the number of publications in the last few years, indicating a clear trend and forecasting a larger number of studies to be published, therefore making the field of research more attractive in the years to come.

A first aspect reflected by our analysis is the relatively low number of studies including aspects regarding global warming from the scientific literature studying water sustainability. Only 6% of the scientific articles studying water sustainability considered global warming as an important factor, indicating that this field of research seems to be incipient and there is a lot more to be found regarding the relations between the two scientific concepts.
The 137 scientific articles included at the end of the selection process are the work of 541 authors, of which only three authored at least three papers and only 26 authored at least two, indicating that the investigated research field is more or less a marginal interest of the large majority of the researchers involved. In addition, we identified that there is a strong dispersal inside the academic community implied in the selected field of research, consistent with the previously presented impression of incipience. A very large number of scientific journals are publishing relatively disparate information and a coherent framework of research and publishing seems to be absent. Given the fact that the temporal trends in publishing and citation indicate a strong growth in the recent period, most likely we will be able to see more coherence in the near future, both in research and in publishing, where the two most dominant publications are WATER and Sustainability, suitable hosts for scientific papers in the field.

US authors are the most influential, leading by far the total number of articles (4.5 times more than the next country involved in the field), citations (seven times more than the next country involved in the field) and in articles published by individual researchers (the only authors with four articles are from the USA). In addition, four of the five most cited papers are published in Proceedings of the National Academy of Sciences of the United States of America, further indicating the US dominance in the analyzed field of research.

The journals with the highest number of articles are Sustainability and WATER, both with nine articles published, a somehow logical approach given the aims and scopes of the two journals. However, a very large number of journals are hosts to our article selection, further indicating the dispersal of scientific information and contributing to the incipience idea discussed before in relation to the very low percentage of article relating water sustainability to global-change problematics and to the very low number of authors with more than two studies published in the field.

The most influential papers present either models of water depletion and increased dryness (a prediction of water depletion in the context of increased water consumption [17]; a model of increased dryness [18]; a global water-resources model influenced by the socio-economic system [25]; and a model of resource depletion in the Colorado River Basin [19]) or frameworks for future water-management practices (a framework for reducing unsustainable water consumption [16]; and a framework for future water-management practices in the context of new challenges [18]), indicating the main interests in relating water sustainability and global warming.

The keyword co-occurrence analysis pointed out an imbalanced distribution, with almost half the studies investigating the present impact of global warming on water sustainability and its effects on water supply and ecosystem functioning, a large proportion of the evaluated studies being focused on “now” and “here”, identifying local or regional problems regarding water sustainability and proposing a post-hoc solution to an already existing problem. The most important trend must be the prevention of water-supply problems and the creation of sustainable solutions for the near-to-medium future, addressing the problems before they can act. The temporal overlay showed that the scientific group involved in studying the field we analyzed is gradually shifting to such an approach.

The most important gap we identified in the selected field of research is the almost total absence of studies investigating the importance of preserving natural habitats as key factors is achieving water-sustainability goals, an aspect of high importance in areas with extensive anthropic impact and a strong presence of urbanized areas, both in intensity and extension. Similarly, we can observe a lack of articles studying the role of supporting natural dynamics as a factor for increasing the quality of aquatic habitats, the main aspects to take into account being spontaneous renaturalization, secondary successions, or the lack of anthropic interventions in already affected areas, and the relations between the presented aspects and future improvements in water sustainability at low spatial scales.

Finally, we observed a relatively low interest in addressing the cultural problems attached to water-sustainability issues, and a more economically oriented approach. Es-
especially in developing countries, a consistent part of the problem is the improper education of the general population regarding sustainable water use and this factor must be taken into consideration in future studies, alongside agricultural, industrial and climatic factors.

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