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# Ancestral water management: An analysis of scientific output using bibliometrics and graph theory

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**ABSTRACT**

The study aimed to examine, using graph theory and bibliometric analysis, scientific output related to ancestral water management. The methodological development comprised two phases. The initial phase entailed the scientific mapping of the area under investigation through a bibliometric analysis of scientific output recorded in Scopus and Web of Science. The subsequent phase entailed a network analysis, which facilitated the identification of the most salient documents concerning ancestral water management and the delineation of the predominant perspectives that currently inform research in this domain. The results indicated that 43% of the research conducted in this field published in the last 5 years. A review of scientific output by country revealed that the United States and China were leading nations in scientific production. The concept of co-occurrence networks substantiated the correlation between an adequate water supply and its effective management, as well as the sustainability of water resources, soil, irrigation, and, consequently, agricultural crops. The network analysis yielded two perspectives that merited further investigation in future research: firstly, the experiences and lessons from ancient cultures' water management that were relevant to the present, and secondly, the structures and use of raw materials in ancestral hydrotechnologies. The potential for future research on ancestral water management was considerable, particularly in terms of articulating lessons learned from the past and current concerns.

**Keywords:** ancestral water technologies; ancestral water management; sustainability; water supply; bibliometric analysis; graph theory.

## 1. INTRODUCTION

Worldwide, water scarcity (Deconinck *et al.*, 2021; Leonel & Tonetti, 2021; OECD-FAO Agricultural Outlook 2016-2025, 2016; OECD/EU, 2020), the energy crisis (Altieri & Nicholls, 2020; Dutta *et al.*, 2020; Giraldo-Díaz, 2020; Ordonez C. Song I.-Y., 2019; Vallejo-Cabrera *et al.*, 2021), biodiversity loss (Agricultura, 2018; FAO *et al.*, 2020; Organización de las Naciones Unidas para la Agricultura y la Alimentación, 2004; Rosa & Collado, 2020), and soil degradation (Callaham & Stanturf, 2020; Carvalheiro *et al.*, 2021; Cortes, 2018; Deepa *et al.*, 2020) are leading to the exploration of both old and new technologies that can respond to the challenges facing today's societies (Altieri & Nicholls, 2020; Giménez Cacho *et al.*, 2018; Giraldo-Díaz *et al.*, 2022; Giraldo & Rosset, 2021; Mooney & ETC,

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2019; Nieto-Gómez *et al.*, 2015; Sánchez, 2015; Trendov *et al.*, 2019).

In this context, the water management practices of the world's ancient peoples are becoming increasingly interesting (Sevilla, 2018; Toledo & Barrera-Bassols, 2008). A global perspective reveals that there are ancestral experiences related to the utilization of hydrotechnologies that facilitate the fulfillment of communities' and agricultural crops' water requirements (Fernandes *et al.*, 2014; Moreira-Segura *et al.*, 2015; OECD, 2012a; Organización de las Naciones Unidas para la Alimentación y la Agricultura -FAO, 2013). The global agrifood system is the primary consumer of water on the planet, with estimations indicating its consumption of water amounts to 70% of the global total (Lu *et al.*, 2021).

Despite the significance of the subject of ancestral water management, there is currently no review that demonstrates the evolution of this domain of knowledge and provides an overview of research trends. For instance, the work of Selvaraj *et al.* (2022) explores the scientific, architectural, artistic, and functional dimensions of the primary step wells in India that have either disappeared or lost their relevance due to human population expansion and environmental stress. Researchers such as Saqib *et al.* (2022) have conducted studies that focus on the analysis of water filtration using traditional ceramics or clay pots (hollow cylindrical containers). Research has also been conducted on wastewater treatment (Lu *et al.*, 2021) and its implications for public health (Escudero *et al.*, 2021; Leonel & Tonetti, 2021). Additionally, studies have examined the use of plant species in bioremediation (Kumar & Sharma, 2020; Xi *et al.*, 2021).

As indicated by Valipour *et al.* (2020) and Yin *et al.* (2022), other studies have emphasized the theme of ancestral water management and its applicability to the strengthening of governance and environmental sustainability. Furthermore, these studies have discussed the recovery of ancient inventions, such as the qanat, an underground tunnel system where water flows by gravity down a slight slope in arid and semiarid areas for at least 5,000 years. The origins of qanats can be traced back to ancient Iran, from which they disseminated extensively throughout the Middle East, reaching regions as far as North Africa, Spain, Italy, and South Asia, particularly Iran (Esmaeili *et al.*, 2022). Concomitantly, research has been conducted that focuses on the teachings of ancient metropolitan civilizations that were previously highly developed (Ahmed *et al.*, 2020; Angelakis *et al.*, 2020; Cun *et al.*, 2019; Gates-Foster *et al.*, 2021; Haug, 2021; Khan *et al.*, 2021; Remmington, 2018). The objective of this research is to examine, through graph theory and bibliometric analysis, scientific production related to ancestral water management.

## 2. METHODOLOGY

The methodological development of this research consisted of two phases. The initial phase entailed the scientific mapping of the area under investigation through a bibliometric analysis of scientific output recorded in Scopus and Web of Science (WoS). The subsequent phase entailed a network analysis, which facilitated the identification of the most salient documents concerning ancestral water management. This analysis also enabled the determination of the predominant perspectives that currently inform research in this domain.

### 2.1. Scientific mapping

To carry out a scientific production analysis and mapping, the five bibliometric approaches proposed by Zupic and Čater (2015) were used: citation analysis, word co-occurrence analysis, co-citation analysis, co-authorship analysis, and bibliographic coupling analysis. To obtain a more comprehensive overview of the field, the WoS and Scopus databases were integrated (Echchakoui, 2020), as both are recognized as the leading global databases (Pranckut, 2021; Zhu & Liu, 2020). The search criteria are delineated in Table 1.

The application of search criteria resulted in 308 records in WoS and 463 in Scopus. A total of 436 duplicates were identified, resulting in 614 unique records, with an overlap of 20%. To maximize the retrieval of records within both databases, the search parameters were modified to incorporate the terms (TITLE-ABS-KEY("water management") AND TITLE-ABS-KEY(ancient)), and the publication period was limited to between 2000 and

| | Databases | |
|---|---|---|
| | **Web of Science** | **Scopus** |
| Temporary coverage | 2000-2022 | |
| Document type | Articles, books, book chapters, and conference proceedings | |
| Search fields | Title, abstract, and keywords | |
| Search equation | TITLE-ABS-KEY(“water management”) AND TITLE-ABS-KEY(ancient) AND PUBYEAR >= 2000 AND PUBYEAR <= 2022 | TITLE-ABS-KEY(“water management” AND ancient) AND PUBYEAR > 1999 AND PUBYEAR < 2023 |
| Results | 308 | 463 |
| Total result after reducing overlap | 614 | |

**Table 1.** Search criteria.

2022, in two languages (English and Spanish). An analysis of publications on this subject indexed in WoS and Scopus revealed that 94% of them are in English, 2% are in French, and the remaining 1% are in other languages. This is due to the fact that publication in English is a prerequisite for indexing in databases, with the objective of enhancing the visibility of journals and authors (Vera *et al.*, 2019).

The Bibliometrix tool (Aria & Cuccurullo, 2017) was utilized for the bibliometric analysis. Due to its extensive array of functionalities, this instrument facilitates the management of multiple databases and has been utilized and substantiated in a multitude of scientific studies (Acevedo *et al.*, 2020; Di Vaio *et al.*, 2021; Duque, Samboni, *et al.*, 2020; Duque, Trejos, *et al.*, 2021; Landinez *et al.*, 2019; Queiroz & Fosso Wamba, 2021; Secinaro *et al.*, 2021; Tani *et al.*, 2018; Trejos-Salazar *et al.*, 2021).

## 2.2. Network analysis

To build the knowledge network in this subject area, the *R* computer program was used. The bibliographic references were extracted and structured by creating a citation network based on graph theory, a technique that allows the typology and characteristics of the network to be analyzed, as well as the documents that comprise it (Wallis, 2007; Yang *et al.*, 2016). Subsequently, three bibliometric indicators were calculated: the *Indegree,* which indicates how many times a document has been cited by others (Wallis, 2007); the *Outdegree,* which reflects how many times a node (document) cites others or the number of outgoing connections (Wallis, 2007); and *Betweenness,* which measures the degree of intermediation or centrality of a document within the network, identifying those texts that are not only cited but also cite multiple sources (Freeman, 1977; Zhang and Luo, 2017).

The knowledge network in this area consists of all documents retrieved from databases along with their references, which means including works from various sources beyond WoS and Scopus, as well as other databases and scientific publications. This network analysis, also known as a citation map, enables the visualization of the field’s structural framework, thereby facilitating the identification of thematic subareas or research trends (Gurzki and Woisetschläger, 2017; Zuschke, 2020). To graphically represent the knowledge network related to ancestral water management, we employed the Gephi tool (Bastian *et al.*, 2009).

The records comprising the network were analyzed using the *indegree, outdegree,* and *betweenness* indicators, facilitating the classification of the works through the use of the tree analogy (Robledo *et al.*, 2014; Rubaceti *et al.*, 2022; Valencia *et al.*, 2020). At the roots of the field, represented by a high indegree, are the classic documents with a hegemonic theoretical weight. These documents are characterized by being widely cited but not necessarily citing others (Wallis, 2007). The trunk, associated with high betweenness, groups together structural works that link the theoretical basis of the classics with more recent research; these documents are cited and cite others (Zhang and Luo, 2017). Finally, the leaves, which have a high outdegree, include recent publications that cite numerous sources, reflecting current trends in the field and shaping emerging research fronts (Wallis, 2007). This tree structure-based methodology has been previously applied and validated in various studies (Buitrago *et al.*, 2020; Cabrera-Otálora *et al.*, 2022; Clavijo-Tapia *et al.*, 2021; Correa Espinal *et al.*, 2011; Duque, Meza, Giraldo, *et al.*, 2021; Duque, Meza, Zapata, *et al.*, 2021; Duque, Toro, *et al.*, 2020; Duque & Cervantes-Cervantes, 2019; Ramos *et al.*, 2021; Rubaceti *et al.*, 2022; Torres *et al.*, 2021).

## 3. RESULTS AND DISCUSSION

Ancestral water management has become increasingly salient for humanity, as evidenced by the steady increase in scientific publications on this topic. In the preceding half-decade, 43% of the research conducted in this field has been published in WoS and Scopus (Table 2).

| Year | WoS | Scopus | Total |
|---|---|---|---|
| 2022 | 23 | 29 | 39 |
| 2021 | 37 | 57 | 70 |
| 2020 | 30 | 31 | 47 |
| 2019 | 33 | 41 | 59 |
| 2018 | 28 | 29 | 45 |
| 2017 | 26 | 31 | 44 |
| 2016 | 17 | 21 | 30 |
| 2015 | 13 | 22 | 30 |
| 2014 | 18 | 31 | 41 |
| 2013 | 16 | 25 | 34 |
| 2012 | 7 | 16 | 18 |
| 2011 | 7 | 17 | 19 |
| 2010 | 8 | 25 | 28 |
| 2009 | 10 | 13 | 17 |
| 2008 | 5 | 14 | 16 |
| 2007 | 5 | 25 | 27 |
| 2006 | 3 | 5 | 7 |
| 2005 | 3 | 6 | 7 |
| 2004 | 1 | 4 | 5 |
| 2003 | 1 | 3 | 4 |
| 2002 | 4 | 9 | 11 |
| 2001 | 2 | 2 | 4 |
| 2000 | 4 | 6 | 9 |
| **Total** | **611** | | |

**Table 2.** Annual scientific output on the topic of "ancestral water management."

The topic exhibits an annual growth rate of 6%. The challenges currently faced by modern science and technology in addressing pressing issues have prompted a search for solutions grounded in the successful experiences of communities that have been tested over centuries. Projections indicate that by 2050, the global population will surpass 10 billion, with over 40% facing severe water stress (OECD, 2022a).

### 3.1. Scientific output by country

An analysis of scientific output by country reveals that the United States and China are leaders in traditional water management, with 14% and 10%, respectively (Table 3). The subsequent countries in this order are Italy, the United Kingdom, and Greece, each

| Country | WoS | Scopus | Total | % |
|---|---|---|---|---|
| United States | 71 | 55 | 88 | 14 % |
| China | 19 | 57 | 61 | 10 % |
| Italy | 16 | 27 | 33 | 5 % |
| United Kingdom | 26 | 22 | 32 | 5 % |
| Greece | 13 | 25 | 29 | 5 % |
| Germany | 16 | 21 | 27 | 4 % |
| Spain | 12 | 14 | 21 | 3 % |
| Belgium | 19 | 3 | 20 | 3 % |
| India | 6 | 18 | 19 | 3 % |
| Australia | 12 | 9 | 14 | 2 % |
| Netherlands | 10 | 5 | 13 | 2 % |
| France | 8 | 7 | 12 | 2 % |
| Poland | 6 | 5 | 9 | 1 % |
| Iran | 3 | 6 | 8 | 1 % |
| Denmark | 6 | 3 | 7 | 1 % |
| Sweden | 5 | 3 | 7 | 1 % |
| Canada | 3 | 5 | 7 | 1 % |
| Sri Lanka | 2 | 5 | 6 | 1 % |
| Hungary | 5 | 2 | 5 | 1 % |
| Israel | 3 | 4 | 5 | 1 % |
| Austria | 2 | 4 | 5 | 1 % |
| Chile | 3 | 1 | 4 | 1 % |
| Japan | 2 | 3 | 4 | 1 % |
| Slovenia | 2 | 2 | 4 | 1 % |
| Malaysia | 0 | 4 | 4 | 1 % |

**Table 3.** Scientific output by country on the topic of "ancestral water management."

with 5%. It is noteworthy that 5 of the 20 countries with the highest scientific output are also among the top 10 countries with the most significant water scarcity. According to the OECD (2012b, 2022a), Greece, Spain, Iran, Israel, and Chile are the countries in question. The heightened interest exhibited by nations in the domain of ancestral water management is concomitant with the projected escalation in global water demand, which is anticipated to rise by 55% by the year 2050. This augmentation in demand is poised to jeopardize the integrity of aquifers (OECD, 2022b).

## 3.2. Scientific output by authors

The three most prominent authors, both in terms of number of publications and citations, are *Angelakis, Andreas Nikolaos*, from Greece; *Dunning, Nicholas P.* and *Scarborough, Vernon L.*, both from the United States (Table 4).

| Authors | Total records | Membership |
|---|---|---|
| Angelakis, Andreas Nikolaos | 28 | HAO-Demeter, Heraklion, Greece |
| Dunning, Nicholas P. | 10 | University of Cincinnati, United States |
| Scarborough, Vernon L. | 8 | University of Cincinnati, United States |
| Verheyen, Kris | 8 | Ghent University, Belgium |
| Wang, Yanling | 8 | The Third Affiliated Hospital, Sun Yat-sen University, Guangzhou, China |
| Mays, Larry Wesley | 7 | Arizona State University, United States |

**Table 4.** Authors with the highest output on the topic of "ancestral water management."

The co-authorship network confirms the authorship of Koutsoyiannis D and his network. Crouch, English, Wulff, Helms, and Beaumont cite the primary authors Angelakis, Jansen, Hodge, and Iofrano in the initial instance (Figure 1).

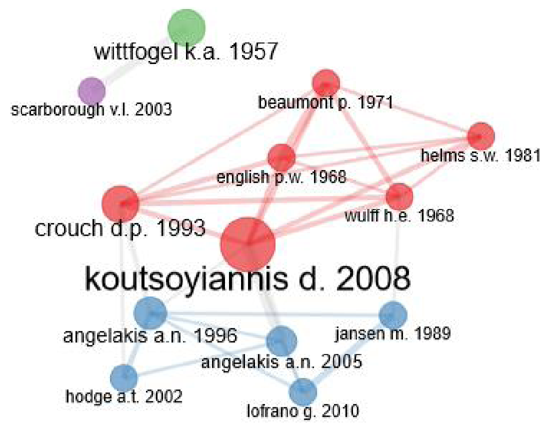


**Figure 1.** Co-authorship network on the topic of "ancestral water management."

## 3.3. Scientific output by journals

An analysis of the most relevant journals in the field of traditional water management reveals the importance of this issue at the global level (Table 5). The following factors have been identified as contributing to the predominance of journals in quartile 1 of the Scimago Journal Rank (SJR): concerns regarding water loss due to natural disasters and climate change, water demand from agriculture, the impact of urban growth, the use of water as an alternative energy source, and the quantity and quality of water available for human use. Of the 20 most relevant journals in the field, 17 are published in three countries: the United Kingdom (7), the United States (5), and the Netherlands (5); 2 are from Germany; and 1 is from Switzerland.

## 3.4. Word co-occurrence network

The co-occurrence network (Figure 2) substantiates the correlation between an adequate water supply and its effective management, on the one hand, and the sustainability of water resources, soil, irrigation, and, consequently, agricultural crops, on the other. The exhibition also showcases the origins and primary historical developments of ancient civilizations centered around water, with a particular focus on China, Greece, and Asia in general.

| Journal | Records | | Total | Scimago Journal Rank | | | Country |
|---|---|---|---|---|---|---|---|
| | WoS | Scopus | | Quartile | SJR | H-Index | |
| *Water Science and Technology: Water Supply* | 0 | 9 | 9 | Q3 | 0,343 | 42 | United Kingdom |
| *Agricultural Water Management* | 7 | 0 | 7 | Q1 | 1,49 | 139 | Netherlands |
| *Journal of Arid Environments* | 6 | 5 | 7 | Q2 | 0,66 | 122 | United States |
| *World Archaeology* | 6 | 6 | 7 | Q1 | 0,8 | 73 | United Kingdom |
| *Water (Switzerland)* | 0 | 7 | 7 | Q1 | 0,72 | 69 | Switzerland |
| *Wiley Interdisciplina y Reviews-Water* | 9 | 0 | 6 | Q1 | 1,84 | 30 | United States |
| *Geomorphology* | 6 | 0 | 6 | Q1 | 1,21 | 171 | Netherlands |
| *Journal of Field Archaeology* | 6 | 0 | 6 | Q1 | 1,1 | 40 | United Kingdom |
| *Journal of Archaeological Science* | 5 | 6 | 6 | Q1 | 1,44 | 137 | United States |
| *Quaternary International* | 4 | 3 | 6 | Q1 | 0,87 | 113 | United Kingdom |
| *Journal of Archaeological Science-Reports* | 9 | 0 | 5 | Q1 | 0,73 | 32 | Netherlands |
| *Ancient Mesoamerica* | 4 | 3 | 5 | Q1 | 0,53 | 40 | United Kingdom |
| *Journal of Anthropological Archaeology* | 3 | 3 | 5 | Q1 | 1,09 | 73 | United States |
| *Plos One* | 3 | 5 | 5 | Q1 | 0,85 | 367 | United States |
| *International Journal of Global Environmental Issues* | 0 | 5 | 5 | Q3 | 0,27 | 23 | United Kingdom |
| *Science of the Total Environment* | 0 | 5 | 5 | Q1 | 1,85 | 275 | Netherlands |
| *Hydrogeology Journal* | 0 | 3 | 5 | Q1 | 0,84 | 104 | Germany |
| *Antiquity* | 4 | 0 | 4 | Q1 | 1,04 | 80 | United Kingdom |
| *Hydrology and Earth System Sciences* | 4 | 0 | 4 | Q1 | 1,78 | 147 | Germany |
| *Catena* | 3 | 4 | 4 | Q1 | 1,39 | 140 | Netherlands |

**Table 5.** Most relevant journals in the field of "ancestral water management."


**Figure 2.** Word co-occurrence network for the topic "ancestral water management."

## 3.5. Network (tree) of the ancestral water management area

The documents examined in the context of ancestral water management were structured according to the tree of science metaphor (Figure 3), facilitating the classification of 10 documents as classic (roots), 10 documents as structural (trunk), and 27 documents as recent (leaves). To identify research perspectives, the clustering algorithm proposed by Blondel *et al.* (2008) was applied, which allowed two groups to be distinguished. The analysis of these two groups is presented below.

## 3.6. Classic, hegemonic, or seminal (root) documents

One of the foundational texts in this area is that of Wittfogel (1957), who proposes a relationship between water and political power. According to this author, the presence of centralized water control in Asia has enabled the rise of "despotic regimes." The construction of large irrigation infrastructures necessitated centralized forms of governance, thereby facilitating the emergence of hierarchical and despotic states.

In a similar vein, but in a different geographical area, the studies by Koutsoyiannis *et al.* (2008), Angelakis and Spyridakis (1996), and Angelakis *et al.* (2005) provide further insight. These studies posit that the evolution of urban

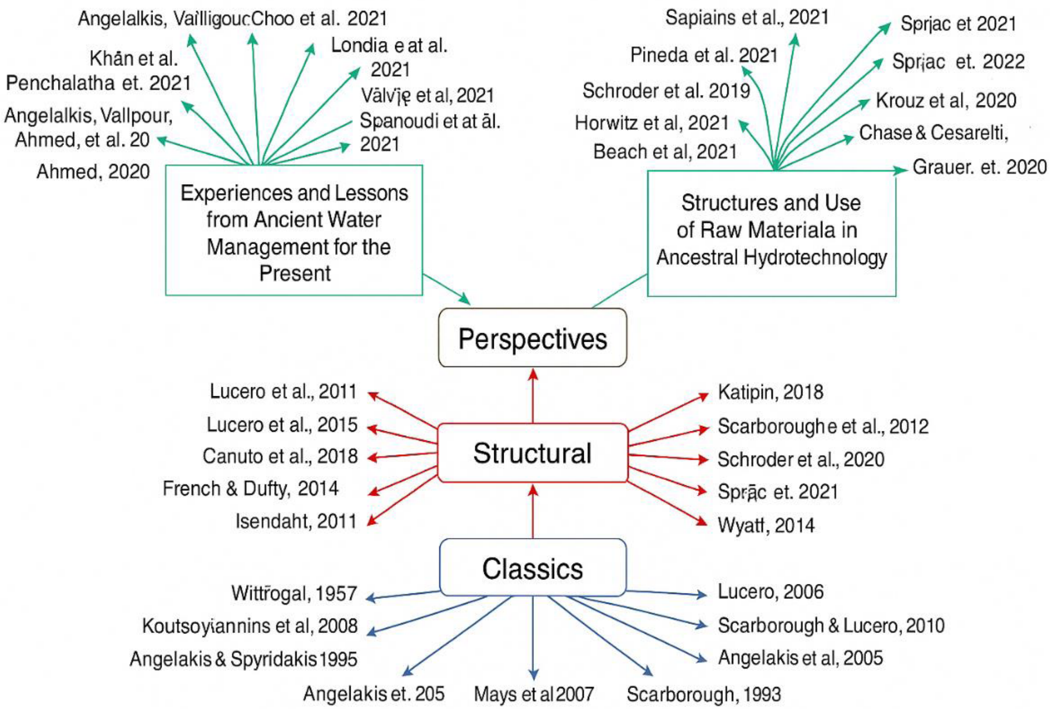


**Figure 3.** Science tree for the topic "ancestral water management."

water management in ancient Greece, which began in Crete during the early Minoan period, led to a series of notable developments both on the mainland and in the Greek islands. These advancements encompass the implementation of hygienic living standards, advanced hydraulic technologies for water transport, flood and sediment control structures, and sustainable urban water management practices that bear a resemblance to contemporary practices. The evolution of water management is also linked to the sociopolitical conditions during the oligarchic periods, as there was an emphasis on the construction of large-scale hydraulic projects. The relevance of such practices and institutions persists in the contemporary era, as the water-related challenges confronting modern societies bear a notable similarity to those experienced in antiquity.

Mays *et al.* (2007) present a comprehensive history of ancient water supply techniques for urban areas, spanning from the earliest civilizations to Roman times. According to the authors, since the earliest civilizations, the utilization of all water sources (rivers, lakes, springs, underground aquifers, and rainwater collection) has been meticulously planned for urban supply. Throughout history, the Greeks and, later, the Romans achieved a high level of water supply technology that greatly influenced modern achievements in water engineering and management.

Scarborough's (1996, 1998) and Scarborough *et al.*'s (2003) studies underscore the Maya's management of water resources in the central Yucatan lowlands and underscore the importance of this understanding for the study of ancient political economy. Scarborough (1998) posits that the pervasive utilization of artificially modified natural depressions for water collection and storage, encompassing both drinking and agricultural applications, served as the foundation for the architecture and monuments of numerous prominent Maya cities during the Classic period (250-900 AD). These elevated centers, designated as "water mountains," were associated with substantial reservoirs that played a critical role in sustaining social and political activities. In this regard, Lucero (2006) documents the ritual histories of commoners, elites, and rulers in the southern Maya lowlands from the Late Preclassic to the Terminal Classic periods. Lucero's research demonstrates how elites and rulers gained political power through the public replication and elaboration of domestic rituals related to water. Furthermore, he demonstrates that political power was contingent on material conditions that Maya rulers could only partially control.

The seminal work of Scarborough and Lucero (2010) has undergone a paradigm shift, shifting the focus from the examination of the relationship between water and politics to the analysis of how communities in the tropics and semitropics survive under conditions of unpredictable rainfall patterns. The paper emphasizes that in the Amazon, Bali, Angkor, the Maya lowlands, and West Africa, people adapt sustainably by constructing water management systems and developing specialized occupations.

### 3.7. Structural documents (trunk)

Among the documents under scrutiny, which are cited reciprocally by the leaves and roots, the focal point of the research endeavors is delineated as an investigation into the means by which ancient communities prevailed or faltered in their water management practices. This inquiry seeks to elucidate lessons that can be applied to contemporary challenges.

Lucero *et al.* (2015) emphasize that in the tropical regions of Southeast Asia and the southern Maya lowlands, water management was crucial for maintaining political power and distributing communities across the landscape between the 9th and 16th centuries. Water played a pivotal role in the material, spiritual, artistic, and ceremonial practices of these communities. The collapse of urban centers in the Maya society of the Classic period was attributed to the inability to organize community life around public ceremonies, games, festivals, and other integrative activities in a cohesive manner (Lucero *et al.*, 2011).

As indicated by numerous studies, the Maya region is characterized by the prevalence of archaeological remains that attest to ancient irrigation and water storage technologies (Canuto *et al.*, 2018; French & Duffy, 2014; Isendahl, 2011; Kaptijn, 2018; Scarborough *et al.*, 2012; Schroder *et al.*, 2020; Šprajc *et al.*, 2021; Wyatt, 2014). The construction and maintenance of infrastructure such as dams, canals, and irrigation ditches necessitated substantial labor force deployment. These endeavors were frequently associated with centralized, state-level administration. These more visible features coexisted with smaller water management technologies that were often managed at the community or household level. In the Maya area of southern Mesoamerica, these ancient technologies manifest in the form of small dams, reservoirs, and other water storage facilities, such as wells, irrigation canals, and agricultural terraces.

### 3.8. Recent documents and perspectives (sheets)

Based on the analysis of the documents in this review, two main research perspectives were identified using the clustering algorithm: (1) experiences and lessons from ancient cultures' water management for the present day and (2) structures and use of raw materials in ancestral hydrotechnologies.

#### 3.8.1. Experiences and lessons from ancient cultures' water management for the present day

A review of the extant literature indicates that the academic community is interested in understanding both ancient water cultures and related hydrostructures (Ahmed *et al.*, 2020). Among these studies, those dedicated to the ancient Egyptian and Greek civilizations, which prevailed in the eastern Mediterranean since prehistoric times, stand out. A comparative analysis reveals numerous parallels and divergences between the two civilizations. A period of coexistence between the two groups occurred from 2000 to 146 BC, despite their geographical separation. Both civilizations were renowned for their commercial prowess and subsequently exerted a profound influence on the civilizations that emerged in that region. Throughout history, both civilizations have established scientific and technological principles, with water management being a primary technology (Ahmed *et al.*, 2020; Angelakis, Valipour, Ahmed, *et al.*, 2021; Hunter, 2021; Penchalaiah *et al.*, 2021; Valipour *et al.*, 2020).

This trend encompasses research on the Neolithic civilizations of Mehrgarh (ca. 7000-2500 BC) and Baluchistan, as well as the Indus Valley (ca. 2500-1500 BC) in the province of Sindh, Pakistan. In these civilizations, rural traditions underwent significant adaptations in response to the increasing frequency of western depressions (winter rains) and monsoon rainfall in the region. The climate of both civilizations was influenced by a multitude of factors, including population growth, resource conflicts, technological advancement, the industrial revolution, the Aryan invasion, deforestation, migration, natural disasters, and sociocultural advancement. The communities residing in both civilizations had highly developed agriculture, sanitation, water management, wells, baths, toilets, shipyards, and flooding systems and were experts in the use of water (Khan *et al.*, 2021).

In this context, studies have been conducted on the methods employed in ancient times for the conservation and reuse of water, as well as on rainwater harvesting, utilization, and desalination (Angelakis, Valipour, Choo, *et al.*, 2021; Londra *et al.*, 2021; Šulyová *et al.*, 2021). In ancient Egypt, the recurrent inundation of the Nile River exerted a profound influence on nascent agricultural practices, which presumably entailed the cultivation of seeds sown into soil that had recently been covered and fertilized with sediment. Conversely, in arid and semiarid regions, farmers leveraged perennial springs and seasonal runoff, operating under conditions starkly divergent from those experienced by riverine civilizations in Mesopotamia, Egypt, India, and the early dynasties of China (Angelakis *et al.*, 2020).

Ancient water harvesting techniques incorporated stepped wells into agricultural and irrigation networks using prefabricated structures, thereby enabling open channels to flow and connect to surface water bodies (Leonel and Tonetti, 2021; Selvaraj *et al.*, 2021). These techniques encompassed the utilization of Persian wheels, non-mechanized agricultural machinery, and an array of other agricultural implements, along with the employment of a diverse array of local building materials, including granite, marble, sandstone, bricks, lime, mud, and wood. In addition, agricultural waste materials such as rice husks were utilized in the production of the brick known as "lakhori." In Alexandria, Spanoudi *et al.* (2021) reported the utilization of reservoirs for the storage of rainwater, spring water, and river water to meet seasonal needs. These reservoirs vary in complexity, ranging from simple structures to large underground reservoirs.

### 3.8.2. Structures and use of raw materials in ancestral hydrotechnologies

This systematic review of the extant literature demonstrates the academic community's interest in learning more about the experiences of ancient societies in terms of infrastructure, raw materials used, and the challenges they faced in managing water. As Somrak *et al.* (2020) have demonstrated, archaeologists working with airborne laser scanning (ALS) data have a marked tendency to rely on manual inspection. In order to achieve a more accurate and effective classification of ancient structures and to differentiate them from their natural environment, it is essential that models and tools be incorporated. The work of Beach *et al.* (2019) describes a large area of ancient Mayan wetland systems in Belize (Central America). These systems were determined to be based on an airborne survey, together with multiple proxies and radiocarbon dates, which revealed the uses and chronology of ancient fields.

Technological advances have made it possible to explore archaeologically unexplored areas (Banasiak *et al.*, 2022; Horowitz *et al.*, 2021; Krause *et al.*, 2019; Pineda *et al.*, 2022; Sapiains *et al.*, 2021; Šprajc *et al.*, 2021, 2022). Šprajc *et al.* (2022) located Chactún, Tamchén, and Lagunita, three important Mayan centers with some unexpected characteristics, in 2013 and 2014, during initial surveys conducted in the northern part of the uninhabited Calakmul Biosphere Reserve in eastern Campeche (Mexico). LIDAR (light detection and ranging) data acquired in 2016 for an area of 240 $km^2$ revealed a completely modified and undisturbed archaeological landscape with a large number of residential groups and widespread modifications related to water management and agriculture. They obtained substantial additional information through field studies and test excavations in 2017 and 2018.

Schroder *et al.* (2020) conducted an evaluation of 458 LIDAR mosaics collected by environmental scientists in southern Mexico. The evaluation utilized NASA's Goddard Space Flight Center's G-LiHT system. These authors describe the results of a comprehensive data processing, inspection, and annotation procedure for the identification and benchmarking of archaeological features. These data facilitate the identification of specific characteristics of the pre-Hispanic Mesoamerican landscape, thereby prompting novel inquiries into the relationship between past settlements and regional cultural, political, and ecological systems. In conclusion, the available data offer significant resources for the discussion of methodologies for the preservation and conservation of archaeological resources in the lowlands, particularly in cases where these resources are not associated with monumental architecture.

Dunning *et al.* (2019) presented a model of three variants of landscape changes attributable to topography, lithology, hydrology, and cultural processes that allow for the documentation of the transformation of the first Maya cities that developed along the edges of large karst or structural depressions (lowlands). The topographic position of the region played a pivotal role in facilitating the effective capture and storage of rainwater by growing populations. This was a critical factor in enabling year-round habitation in the interior regions of the Maya lowlands in Mexico and Central America. The clearance of aged forests from steep terrain has been demonstrated to result in the accelerated erosion and degradation of the margins of the lowlands. These newly created colluvial margins subsequently became the focus of intensive agriculture, thereby helping to support further urban expansion.

The findings of Dunning *et al.* (2019) are consistent with those reported by Chase and Cesaretti (2019), who consider that the Mayan cities of Caracol and Tikal during the Classic period exhibited unique urban morphologies related to water management. To a certain extent, the urban landscape of each city is indicative of its hydrological characteristics. The region's topography, characterized by mountains and karst terrain, has been a pivotal factor in the development of the garden city of Caracol. The strategic exploitation of this terrain by its inhabitants has led to the formation of distinctive anthropogenic landscapes, including agricultural terraces and residential reservoirs. The topography was characterized by a network of dendritic roads and the dispersed placement of monumental nodes. The topography of Tikal features a lower slope and is characterized by a general gentleness. The site's inhabitants constructed a substantial, compact site core and monumental reservoirs. Furthermore, the people of Tikal engaged in low-margin agriculture. The differences in urban form and hydrology influenced the water management strategies employed by both cities, and these environmental characteristics are preserved in the archaeological record.

Within this trend, there is also research that interprets ancestral hydrotechnologies from social and humanistic perspectives. Grauer (2020) proposes that a holistic and relational approach to landscape facilitates a more profound comprehension of the intricate relationships between humans and the environment. His work examines the ecological and social aspects of the landscape of the ancient Mayan city of Aventura, in Belize, in the context of relational ontologies. Through an examination of its spatial context, material content, and associated activities that establish cosmological connections, the author arrives at the conclusion that human relationships underscore the interconnectedness between humans and the environment. This approach precludes the projection of contemporary Western categories of nature and culture onto historical periods. In a similar vein, Nicholson-Sanz's (2020) studies center on the so-called Water Judges (WJ) of San Pedro de Corongo, who are responsible for a political and administrative system for the ritual and practical management of the waters of the river that runs through this municipality, located in an inter-Andean valley in central Peru at 3,150 m above sea level. An analysis of this festival reveals the efficacy of water governance through ritual actions, which are inextricably linked to the ancient relationship between the people of Corongo and their natural environment.

## 4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Based on the literature reviewed, it is confirmed that this is the first systematic review of ancestral water management that applies graph theory to examine scientific output in this field. This analytical approach has made it possible to visualize a network of 771 publications from the period 2000-2022, identifying classic, structural, and recent documents. The latter are particularly important, as they allow us to outline and characterize the main lines of research in the field. The analysis of the network has yielded two perspectives of interest for future research: (1) experiences and lessons from ancient cultures' water management for the present and (2) structures and use of raw materials in ancestral hydrotechnologies.

The countries that lead the production of research in the area of ancestral water management are the United States, China, Italy, the United Kingdom, and Greece. The leadership demonstrated in this study is evident in two ways. First, it is evident in the two databases that were used: WoS and Scopus. Second, it is evident in the literature that was reviewed. Scopus is the database with the highest proportion of scientific output in the area, with 60% of publications, compared to 40% in WoS. With respect to journals, 17 of the 20 most relevant are indexed in quartile 1 of the SJR, reflecting a notable preference for disseminating research on ancestral water management in high-impact publications. The journal with the highest number of publications, nine in total, is *Water Science and Technology: Water Supply,* an organization primarily concerned with the scientific study of water.

The mounting interest within the scientific community in conventional water management is exemplified by the substantial surge in academic productivity over the past 5 years. This period of growth is closely associated with the sustainable development goals (SDGs) promoted by the United Nations (UN) and adopted by countries in 2015. Specifically, research in this area contributes substantially to the realization of goals 6 (clean water and sanitation), 11 (sustainable cities and communities), 13 (climate action), 14 (life below water), and 15 (life on land).

There are numerous prospects for future research on traditional water management, especially those that link lessons learned from the past with current concerns. The following challenges related to water in the future should be taken into account:

- Water supply will be limited and regulated for all users, and water rights and pricing schemes will be reviewed and adapted to changing conditions.
- Greater shares of water will be transferred from agriculture to urban areas, recreational activities, and the environment.
- Increased climate variability will exacerbate water supply problems and increase the uncertainty and unpredictability faced by farmers.
- Land and water degradation may become more substantial and also attract greater public attention.
- More efficient water management practices will be needed at the microlevel, which could also combine broader environmental benefits with economic gains for farmers.
- The farming systems used in irrigated agriculture in arid and semiarid areas should be adapted to lower water availability and poorer water quality.
- New varieties and crops of plants that are adaptable to drier conditions are and will continue to be essential for better water use in agriculture.
- Knowledge of the relationships between water and nutrients and different types of soil will also be essential for proper water management in agriculture.

Concurrently, research avenues are emerging in rainwater harvesting techniques to address the water needs of arid and semiarid regions. It is imperative to direct research efforts toward the development of suitable water governance alternatives, both for the present moment and to anticipate future challenges. Consequently, research endeavors aimed at enhancing comprehension of ancestral water management methodologies will prioritize the applications of hydrotechnologies employed by these ancestral societies. These studies will also seek to identify the raw materials and structures utilized, facilitating a more precise understanding of the technological landscape.

## Conflict of interest

The authors declare that there is no conflict of interest.

## Contribution statement

Conceptualization, research, methodology, validation, resources, original draft writing, review, and editing: Libia Esperanza Nieto Gómez, Reinaldo Giraldo Díaz.

Formal analysis, software, data curation, visualization: Reinaldo Giraldo Díaz.

Supervision, project management, fundraising: Libia Esperanza Nieto Gómez.

### Statement of data consent

The data generated during the research have been presented in the article. ●

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