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# Unconventional Water Resources: Global Opportunities and Challenges

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# Unconventional water resources: Global opportunities and challenges

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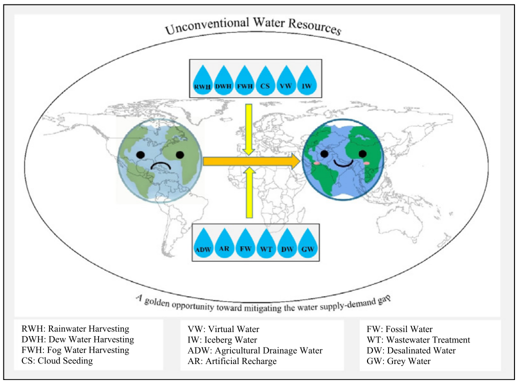
## HIGHLIGHTS

- Twelve general types of UWRs were presented based on literature review.
- The UWRs were categorized as atmospheric, transferred, processed and groundwater resources.
- Global distribution of UWRs utilization depends on climate, socio-economic, cultural, environmental, and political conditions.
- Opportunities and challenges of utilizing UWRs were presented.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Water is of central importance for reaching the Sustainable Development Goals (SDGs) of the United Nations. With predictions of dire global water scarcity, attention is turning to resources that are considered to be unconventional, and hence called Unconventional Water Resources (UWRs). These are considered as supplementary water resources that need specialized processes to be used as water supply. The literature encompasses a vast number of studies on various UWRs and their usefulness in certain environmental and/or socio-economic contexts. However, a recent, all-encompassing article that brings the collective knowledge on UWRs together is missing. Considering the increasing importance of UWRs in the global push for water security, the current study intends to offer a nuanced understanding of the existing research on UWRs by summarizing the key concepts in the literature. The number of articles published on UWRs have increased significantly over time, particularly in the past ten years. And while most publications were authored from researchers based in the USA or China, other countries such as India, Iran, Australia, and Spain have also featured prominently. Here, twelve general types of UWRs were used to assess their global distribution, showing that climatic conditions are the main driver for the application of certain UWRs. For example, the use of iceberg water obviously necessitates access to icebergs, which are taken largely from arctic regions. Overall, the literature review demonstrated that, even though UWRs provide promising possibilities for overcoming water scarcity, current knowledge is patchy and points towards UWRs being, for the most part, limited in scope and applicability due to geographic, climatic, economic, and political constraints. Future studies focusing on improved documentation and demonstration of the quantitative and socio-economic potential of various UWRs could help in strengthening the case for some, if not all, UWRs as avenues for the sustainable provision of water.

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*Abbreviations:* ADW, Agricultural Drainage Water; AR, Artificial Recharge; AUW, Atmospheric Unconventional Water; CS, Cloud Seeding; DW, Desalinated Water; DWH, Dew Water Harvesting; FW, Fossil Water; FWH, Fog Water Harvesting; GW, Grey Water; IW, Iceberg Water; IWRM, Integrated Water Resource Management; LULC, Land Use/Land Cover; PUW, Processed Unconventional Water; RWH, Rainwater Harvesting; SDG, Sustainable Development Goal; TUW, Transferred Unconventional Water; UGW, Unconventional Ground Water; UN, United Nations; UNW, Unconventional New Water; URW, Unconventional Reused Water; UWR, Unconventional Water Resource; VW, Virtual Water; WS, Water Stress; WT, Wastewater Treatment.

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## 1. Introduction

Water scarcity, the long-term mismatch between natural water availability and water demand, is a serious socio-environmental challenge for sustainable development. It is recognized as a potential cause of social conflict within and between countries, which is expected to intensify due to increasing water demands, rapid urbanization, industrialization, and climate change (Kummu et al., 2010; Macedonio et al., 2012). Unconventional Water Resources (UWRs) can be an alternative water source and thus overcome water scarcity. Utilizing UWRs is increasingly growing as an emerging opportunity for solving water resource limitations and can be especially useful in arid and semi-arid areas (Gosling and Arnell, 2016; Yazdandoost et al., 2021).

According to Odendaal, 2009, those sources of water which have not been traditionally used to meet existing water demands can be classified as UWRs. UWRs are supplementary water sources requiring specialized processes such as desalination, rainwater harvesting, and iceberg towing, which may lead to applying appropriate strategies for a specified goal (Qadir et al., 2007). Usually, they are not accessible for consumers through conventional means like surface water or groundwater (Indelicato et al., 1993; Haddad and Mizyed, 2004; Pereira et al., 2009).

Definitions of UWRs in general and individually have undergone significant changes over time. Brewster and Buros (1985) defined UWRs as generally not producing new water, but only developing the potential for treating and using water sources that were previously considered unusable or unavailable, such as saline water, wastewater, and inaccessible water resources. They also referred to rainwater harvesting and weather modification as types of UWR. In the 1990s, UWRs were defined as water resources with specific features, such as high organic matter and microorganism content, or high saline concentration needing treatment or similar processes before use (Indelicato et al., 1993). In the early 2000's, rainwater harvesting was added to the list of UWRs (Jaber and Mohsen, 2001). Buchholz (2008) documented UWRs as saline water, brackish water, agricultural drainage water, wastewater, and water obtained by fog capturing, weather modification, and rainwater harvesting. In the recent literature, UWRs have been considered as any water resources other than freshwater that need new technologies to make them useable as complimentary water sources (Ahmed, 2010; Negm et al., 2018; Ji et al., 2020). A historical account of the use of certain types of UWRs since ancient times can be found in the Annex (Appendix A).

Research has also been undertaken to examine UWRs for water supply in terms of:

i) technical aspects, potential applications, impacts, costs, and regional relevance (Smakhtin et al., 2001),
ii) the use of UWRs and opportunities for achieving food security in water-scarce countries (Qadir et al., 2007),
iii) the possibility for the utilization of UWRs for water supply using desalinated water, treated reclaimed water, imported water and water harvesting (Jaber and Mohsen, 2001).

A particular focus has been on the availability and potential utilization of UWRs in agriculture and landscaping in the Middle East and North Africa (Hussain et al., 2019). Djuma et al. (2016) conducted a systematic literature review to assess the extent of research on UWRs in the Middle East and found an increasing trend in the number of articles addressing UWRs. Here, desalination was the most popular technology used, followed by wastewater reuse.

Thus, extensive research has taken place on the use and usefulness of UWRs in general, but also on specific UWRs and their respective benefits under different circumstances. The current literature indicates that (1) UWRs are studied independently from one another, and comprehensive and collective studies are rare, and (2) UWR applications and their impacts on water scarcity and water supply are often carried out at a case study level rather than globally. There is a lack of an all-encompassing article bringing the collective knowledge together to better understand the distribution of UWRs globally and their potential for closing the water demand-supply gap.

The main objective of this review article is thus to offer a better understanding of the existing research on UWRs by summarizing current literature and offering insights into UWR distribution. Results of this review may enhance awareness around UWRs, with a particular focus on their various respective benefits in different climates, potentially leading to better planning and policymaking. In addition, this article intends to highlight the role that UWRs play on a global scale in addressing water scarcity. In Section 2, the reader can find a description of the method used for the literature review, its numerical interpretation, and the extraction of information to produce global maps of UWR distribution. In Section 3, the literature review results and the mapping are presented. Section 4 puts forward a new classification of UWRs and potential opportunities and challenges for the implementation of UWRs.

## 2. Materials and methods

### 2.1. Data sources

#### 2.1.1. Grey literature

Data about UWRs was collected based on the documents presented in reliable websites such as AQUASTAT-FAOs Global Information System on Water and Agriculture (www.fao.org), Global water intelligence (www.globalwaterintel.com), World Water & Climate Atlas (www.iwmi.cgiar.org), the World Overview of Conservation Approaches and Technologies (WOCAT) (www.wocat.net), the International Water Management Institute (IWMI) (www.iwmi.org), the CGIAR Research Program on Water, Land and Ecosystems (WLE) (www.wle.cgiar.org), (www.gwiwaterdata.com), (www.desalination.com) and (www.fogquest.com).

#### 2.1.2. Literature review

Peer-reviewed articles were accessed through the following databases: Scopus by Elsevier, Web of Science (WOS) by Clarivate Analytics, and ProQuest. We limited the review to articles indexed by the Science Citation Index (SCI), Social Science Citation Index (SSCI), and ProQuest databases published in December 2020. As WOS and ProQuest are of a high quality but have a very limited number of publications, it was decided to only use the Scopus database for further analyses since it has a good amount of quality journals covering an extensive set of international English and non-English publications.

The global distribution of published academic records was created by searching the "topic" domain through the Scopus database. Twelve UWRs keywords were used: *artificial recharge, cloud seeding, desalination, dew harvesting, agricultural drainage water, fog harvesting, fossil water, greywater, iceberg towing, rainwater harvesting, virtual water, and wastewater treatment*. Both English and non-English publications were considered.

Statistical analyses were performed based on the Scopus database, and to evaluate the homogeneity of the time-series of UWRs academic records, Pettitt's test (PT) (Pettit, 1979) was adopted at a 5% significance level. The PT method has been reported in several studies (Taxak et al., 2014; Animashaun et al., 2020) as a nonparametric test that is suitable for assessing the existence of abrupt changes in time series data. In the current study, the PT was used to determine the year in which abrupt changes occurred, from 1971 to 2020. Data analysis based on the PT was carried out using XLSTAT in Excel.

### 2.2. Bibliometric analysis of the literature

Bibliometric analyses are effective research methods and have been used to do quantitative assessment in a specific field of research. In bibliometrics analyses, numerous characteristics of documents, such as co-relationships, distribution, and patterns, can be explored using statistical and mathematical methods. They can also measure the contribution of different aspects of a special research topic (Zhang and Yuan, 2019). The bibliometric analysis provides graphics, and statistical and mathematical evaluations of the scientific publications for the identification of areas and for tracking progress for future research. The literature review recognizes the manifest and background for a specific topic from qualitative data (Zhou et al., 2007). In this study, bibliometric analysis and literature review were combined to provide deeper knowledge of the UWRs' research progress.

To visualize keywords co-occurrence of the research pattern, VOSviewer software was used. The VOSviewer software, designed for the bibliometric analysis, was used to identify the keywords that co-occurred more than five times, based on their relevance score (Sharifi, 2021). Based on the review of 189 papers presented in the Scopus database to retrieve all documents relevant to different forms of UWRs, the following string was developed: "TITLE-ABS-KEY ("non-conventional water*" OR "unconventional water*") AND TITLE-ABS-KEY ("artificial recharge*" OR

**Table 1**
UWRs concepts and definitions.

| UWRs | Definition |
|---|---|
| Artificial recharge water | An effective, anthropogenic technique that can lead runoff surface water for infiltration and following movement to the aquifer for the augmentation of subsurface and groundwater resources through designing various methods to increase the transfer of surface waters into groundwater aquifers to supplement the groundwater resources (Bouwer, 2002; Bhattacharya, 2010; Riad et al., 2011; Prabhu and Venkateswaran, 2015). Finding a potential location for artificial recharge plays an important role and is reliant on different key factors such as rainfall, drainage density, lineament density, slope, soil permeability, land use/land cover, geology, and geomorphology (Senanayake et al., 2016). |
| Agricultural drainage water | Agricultural drainage water is an artificial or natural surface and sub-surface water, which is removed from agricultural areas as excess water and can be considered an unconventional water source (Niaghi et al., 2019). Agricultural drainage water is defined as any water left from land irrigation not involved in growing crops (Zhang et al., 2017). Agricultural drainage water can be a probable source for further irrigation when harvested and prevented from being disposed of as wastewater. However, as water passes through the soil and drainage network, it contains salts, agricultural chemicals, and other pollutants such as pesticides, so it needs to be treated (Barnes, 2014). |
| Cloud seeded water | Cloud seeding is a technique of changing the amount, intensity, and even type of precipitation using processes of weather modification. Cloud seeding processes include dispersing agents into a cloud using rockets, aircraft, and ground-based generators (Chien et al., 2017; Hussain et al., 2019). To improve the collision-coalescence process in warm clouds, the cloud seeding authorities can serve as cloud condensation nuclei (CCN) or serve as ice nuclei (IN) to convert liquid water into ice crystals and strengthen vapor deposition, riming, and aggregation processes in super-cooled clouds (Jensen and Lee, 2008). Water obtained from cloud seeding can be considered as high-quality UWRs. Cloud seeding projects require high technologies in terms of financial costs to be performed correctly and huge investments with technically experienced staff (Qadir et al., 2007; Guo et al., 2015; Jung et al., 2015; Wang et al., 2019). |
| Desalinated water | Defined as eliminated salt from saline water (comprises ocean and sea saline water and brackish groundwater), which is perceived of as being an environmentally damaging and expensive alternative and is affordable only for affluent countries (Pistocchi et al., 2020). Referring to the World Health Organization (WHO), the permitted amount of salt in water is 500 ppm and in exceptional situations is up to 1000 ppm (Eltawil et al., 2009; Abdelmoez et al., 2014). A desalination system aims to clean or purify seawater or brackish water and supply water with total dissolved solids within the permissible limit (< 500 ppm). This is accomplished using several desalination techniques that may be classified into conventional and nonconventional methods (Jones et al., 2019; Elsaid et al., 2020; Ghafoor et al., 2020). |
| Dew water | Dew water is a meteorological phenomenon, which is a common occurrence globally (Kaseke and Wang, 2018). As an unconventional potable resource, it originates from atmospheric humidity that is altered into liquid water on cold surfaces (Monteith, 1957; Beysens, 2006). There is some evidence that plants and small animals in arid and semi-arid environments use dew water, (Gindel, 1965; Steinberger et al., 1989). Investigation on dew water collection has been done many times recently (Jacobs et al., 2002; Berkowicz et al., 2004; Beysens, 2006; Sharan, 2006; Clus et al., 2008; Gido et al., 2016; Kaseke and Wang, 2018). |
| Fog water | Fog water as non-rainfall, suspended water droplets and moisture in the atmosphere or near the Earth's surface is available in fog-prone areas and is a high-quality source of unconventional water, which is an important component of the water cycle in water-scarce regions. As a source of potable water, fog-water harvesting using innovative techniques could be a sustainable strategy for providing drinking water for human consumption and environmental ecosystems, which is vital for water harvesting within Integrated Water Resources Management (IWRM) (Olivier, 2004; Rajaram et al., 2016; Gürsoy et al., 2017; Kaseke and Wang, 2018; Karimidastenaei et al., 2020). |
| Fossil water | Fossil water, or paleowater, is a valuable finite and non-renewable UWR. It is ancient water that can be found in undisturbed spaces, such as groundwater in an aquifer and subglacial lakes. This ancient freshwater was formed eons ago and surrounded underground in enormous reservoirs, or aquifers which were established under past climatic and geological conditions (Margat et al., 2006). It provides a significant source of groundwater in water-scarce areas. Fossil water reservoirs are sealed and avoid further water recharge or important outflows (Maliva and Missimer, 2012). These fossil aquifers are often geologically restricted at their lower and upper limits by impermeable rocks, meaning that as soon as it has been extracted, it is gone forever, at least on a human timescale. The exploitation of this type of non-renewable source is commonly referred to as groundwater mining (Omran, 2017). |
| Greywater | Greywater is defined as household wastewater which is generated from all domestic wastewater (e.g., wastewater from bathtubs, hand basin, showers, laundry machines, kitchen sinks or dishwashers), not including toilet flushing water (Boano et al., 2020). In water-scarce regions, treated greywater can reduce water stress as an alternative UWR for non-potable uses. Greywater treatment needs high technological treatments to remove contaminants, including micropollutants related to the use of many personal care products (Patel et al., 2020). |
| Rainwater | Rainwater Harvesting (RWH) is a common and traditional approach globally, which is being carried out for domestic use, groundwater recharge, and small-scale agricultural use, especially in rain-fed agriculture (Mucheru-Muna et al., 2017; Toosi et al., 2020). Due to the lack of precipitation and its unfit Spatio-temporal distribution, RWH is one of the UWRs that can be used in arid and semi-arid regions. (Glendenning et al., 2012; Sepehri et al., 2018; Rahaman et al., 2019). Using rainwater has advantages over other sources, for example, rainwater harvesting in the rainy seasons provides a source of water for when other sources of water, including groundwater, are scarce (in the dry seasons). Also, RWH enables the control of flood flows in areas with heavy rainfall and flooding (Rosmin et al., 2015). Rainwater can be collected from rooftops and non-rooftop areas and can be used in settlements and cultivated areas (Ngigi, 2003; Helmreich and Horn, 2009). |
| Iceberg water towed | Is a type of UWR, which can be used as melted iceberg water and then transferred to the places that need water, or it can be towed to arid and semi-arid places which suffer from water scarcity (Marchenko and Eik, 2012; Yulmetov and Løset, 2017). Iceberg water is the purist unconventional water in the world (Eik and Marchenko, 2010). Iceberg water is offering a great new source for those who do not want to carry out any pre-use processes in terms of increasing the water quality. In a world where the purity of even bottled water is questionable, iceberg-melted water ensures that the water you are drinking is pure and pristine (Eik and Marchenko, 2010; Karimidastenaei et al., 2021). |
| Wastewater | Wastewater is any source of water that has been contaminated by human utilization, from a combination of industrial, agricultural, commercial, and domestic activities. Treated wastewater is one of the most important UWRs (Almanaseer et al., 2020). Treated wastewater is used in agriculture (for crop irrigation), urban landscape irrigation, and industries. It has been used in water-scarce regions, especially in semi-arid and arid regions (Adewumi et al., 2010; Baawain et al., 2020). But public and especially farmer's approval matters, as they are directly impacted by the costs and consequences of these projects (Leviston et al., 2006; Nancarrow et al., 2008; Domènech and Saurí, 2010). Recently, due to freshwater shortage problems, public acceptance has become more positive towards wastewater reuse, with previous concerns becoming less of an issue (Davarnejad et al., 2018; Davarnejad and Karimi Dastnayi, 2019; Karimidastenaei et al., 2020). |
| Virtual water | Virtual water was first introduced by Allan (Allan, 1993) and can be defined as the amount of fresh water that is used to produce goods and services along supply chains. This includes water used in the import of goods, e.g., meat, rice, and cane sugar, which need substantial amounts of water to produce them. Based on this definition, virtual water took a few years to enter global water resource assessments (Horlemann and Neubert, 2006; Wichelns, 2010) and it is one of the UWRs which may be useful for arid regions, as when they import goods from other regions, they are also importing water (Zhao et al., 2020). Physical transfer water and virtual water are used to supply enough water and can be included as a possible option for arid regions (Winpenny et al., 2010). |

"cloud seeding*" OR "desalinate*" OR "dew*" OR "drainage water*" OR "fog*" OR "fossil water*" OR "greywater*" OR "iceberg*" OR "rainwater*" OR "virtual water*" OR "wastewater*") AND TITLE-ABS-KEY (management OR "water scarcity" OR "water supply" OR "water demand" OR policy OR sustainability OR SDG) AND (EXCLUDE (PUBYEAR, 2021))". The keywords with fewer than five occurrences were excluded. Of the 2021 items, only 130 terms met this threshold. The terms were then manually screened to eliminate words that discussed research process and synonyms, and the final keywords were 21.

### 2.3. Distribution maps of UWRs utilizations

The current literature provides the following forms of UWRs: Artificial Recharge (AR), Agricultural Drainage Water (ADW), Cloud Seeded Water (CDW), Desalinated Water (DW), Dew-Water (DW), Fog-Water (FW), Fossil Water (FW), Greywater Treated (GT), Iceberg Towed Water (ITW), Rainwater Harvesting (RWH), and Wastewater Treated (WT). Table 1 provides their definitions.

Virtual Water (VW) as an unconventional water source created some controversy and divided opinions. The concept has been in discussion for more than two decades, with contrasting opinions on the concept and its application. Ye et al. (2018) mentioned that virtual water can be a part of physical water resources to alleviate water stress. Horlemann and Neubert (2006) and Wichelns (2010) have pointed out that it has been a couple of years since virtual water entered global water resource assessments. In this study, based on the concept and the idea of physical transfer of virtual water as an unconventional resource, it was considered as a form of unconventional water by importing goods from other regions.

Global distribution maps of these eleven UWRs were created based on the information extracted from the articles shown in Table 2. Articles were selected based on the following criteria: (1) it had to be an English language article, and (2) the article had to describe a UWR specific project. The list is therefore certainly incomplete and is only an approximation of UWR utilization globally and historically.

Global UWRs utilizations information about artificial recharge, cloud seeded water, dew water, fog water, fossil water, greywater treated, iceberg towed water, and rainwater harvesting was obtained based on data presented in the literature review. The available data for the above-mentioned UWRs was related to each country. According to Deng et al. (2021), all imports and exports of virtual water were considered for virtual water trades (traded volume) between countries. Utilizations data and information about agricultural drainage water, desalinated water, and treated wastewater were obtained based on the documents presented on reliable websites from AQUASTAT-FAOs Global Information System on Water and Agriculture (http://www.fao.org/aquastat).

## 3. Results

### 3.1. Quantitative results of the literature review

The number of publications for Scopus search engine can be found in Table 3. As all the desired data existed in Scopus, the statistical analyses were performed on this data.

A total of 643,101 academic records relating to different types of UWRs between January 1971 and December 2020 were found by the Scopus database. The number of published records increased over time and was highest in 2020. The highest number of publications (61% of the total records) originated from China (130,952), followed by the USA (77,298), India (36,400), Spain (22,785), Iran (21,769), the UK (20,501), Germany (18,915), Canada (18,721), and Australia (17,503) (Fig. 1). Although the conducted literature review was performed by searching the "topic" domain using the previously mentioned keywords on the WOI, Scopus, and ProQuest, and the data on global maps was collected through the literature review, FAO, and different websites, there may still be some relevant literature and data that was not acquired.

**Table 2**
Existing location and databases used in worldwide UWRs utilizations which were used to make Figs. 3 and 4.

| UWRs | References |
|---|---|
| Artificial recharge water | Harpaz (1971); Brown and Signor (1973); Clark and Kneeshaw (1983); Kimrey (1985); Levin et al. (1988); Koutsos (1988); Mukhopadhyay et al. (1994); Wright and du Toit (1996); Schöttler (1996); Hassan and Bhutta (1996); Zubari (1999); Von Hoyer et al. (2000); Haeffner et al. (2001); Gale et al. (2002); Bouwer (2002), Ghayoumian et al. (2007); Hida (2007); Sherif and Kacimov (2007); Delinom (2008); Barber et al. (2009); Al-Assa'd and Abdulla (2010); Saxena et al. (2010); Igboekwe and Ruth (2011); Hamad (2012); Salem et al. (2012); Sayit and Yazicigil (2012); Zakhem and Hafez (2012); Zektser et al. (2012); Kareem (2013); Masciopinto (2013); Arras et al. (2014); Teatini et al. (2015); Zaidi et al. (2015); Zhang et al. (2015); Benseddik et al. (2017); Sprenger et al. (2017); Gesim and Okazaki (2018); Cadamuro et al. (2020); Mohammadzadeh-Habili and Khalili (2020). |
| Agricultural drainage water | FAO (http://www.fao.org/aquastat); Wang et al. (2020). |
| Cloud seeded water | Godson et al. (1966); Rakovec et al. (1990); Dore et al. (1992); Bigg (1997); Mather et al. (1997); Ryan and King (1997); Bruintjes (1999); Yee (1999); Murty et al. (2000); Al-Fenadi (2001); Stauffer Jr. (2001); Andrei et al. (2002); Breed et al. (2005); Khalili et al. (2008); Dessens et al. (2009); Guo and Zheng (2009); Simms (2010); Seifert et al. (2012); Zoljoodi and Didevarasl (2013); Freud et al. (2015). |
| Desalinated water | FAO (http://www.fao.org/aquastat); Lattemann et al. (2010); Gao et al. (2017); Jones et al. (2019). |
| Dew water | Msangi, 1987; Muselli et al. (2002); Sharan (2006); Sharan et al. (2007); Vogel and Müller-Doblies (2011); Sarparast et al. (2014); Khalil et al. (2014); Gałek et al. (2016); Carvajal et al. (2018); Beysens (2018); Carvajal et al. (2018); Atashi et al. (2020); Di Bitonto et al. (2020); Gurera and Bhushan (2020). |
| Fog water | Goncalves and Cunha (1992); Al-Jayyousi and Mohsen (1999); Martorell and Ezcurra (2002); Olivier and De Rautenbach (2002); Holder (2004); Sharma (2006); Noman and Al-Jailani (2007); Mileta et al. (2007); Abdul-Wahab and Lea (2008); Marzol and Sánchez (2008); Marzol et al. (2011); Klemm et al. (2012); Davtalab et al. (2013); Fessehaye et al. (2014); Ngaina et al. (2014); Vuollekoski et al. (2014); Dodson and Bargach (2015); Fessehaye et al. (2015); Ritter et al. (2015); del Río et al. (2017); Fessehaye et al. (2017); Carrera-Villacres et al. (2017); Salem et al. (2017); Qadir et al. (2018); Morichi et al. (2018); Shi et al. (2018); Shrestha et al. (2018); Kaseke and Wang (2018); Echeverría et al. (2020); Villacrés et al. (2020); Gebru et al. (2021) |
| Fossil water | Foster and Loucks (2006); UNESCO (2009); Jasechko et al. (2017). |
| Greywater | Dixon et al. (1999); Smith and Stammerjohn (2001); Günther (2000); Faruqui and Al-Jayyousi (2002); Al-Jayyousi (2003); Lazarova et al. (2003); Prathapar et al. (2005); Rueedi et al. (2005); Exall et al. (2006); Jamrah et al. (2006); Madungwe and Sakuringwa (2007); Roman et al. (2007); Friedler (2008); Jimenez and Asano (2008); Zhang et al. (2009); Domènech and Saurí (2010); Paris and Schlapp (2010); Pinto and Maheshwari (2010); Al-Maskati (2011); Al-Wabel (2011); Mourad et al. (2011); Al-Mughalles et al. (2012); EL-Jumaily and Jalal (2012); Leung et al. (2012); Abd Alaziz and Al-Saqer (2014); Matos et al. (2014); Oron et al. (2014); Redwood et al. (2014); Symonds et al. (2014); Shamabadi et al. (2015); Elmeddahi et al. (2016); Giresunlu and Beler Baykal (2016); Chowdhury and Rajput (2017); Lambert and Lee (2018); Lee and Lambert (2018); Lefebvre (2018); Taemthong (2018); Elkiran et al. (2019); Batisha (2020); Craddock et al. (2020); Ullah et al. (2020). |
| Rainwater | Poesen and Lavee (1997); Hatibu et al. (2000); Li et al. (2000); Kumar et al. (2006); Tal (2006); Abbott et al. (2007); Kahinda et al. (2007); Solomon and Smith (2007); Despins et al. (2009); Li et al. (2010); Roebuck et al. (2011); Rowe (2011); Biazin et al. (2012); Areerachakul (2013); Hartung and Akkerman (2014); Lo and Koralegedara (2015); Ammar et al. (2016); da Costa Pacheco et al. (2017); Teston et al. (2018). |
| Iceberg water towed | Lefrançois et al. (2008); Spandonide (2012); Spandonide (2009). |
| Virtual water | Feng and Hubacek (2015); Deng et al. (2020); Wang et al. (2020). |
| Wastewater | FAO (http://www.fao.org/aquastat); Sato et al. (2013). |

**Table 3**
The number of publications on Scopus search engine.

| UWRs | Scopus |
|---|---|
| Artificial recharge | 6850 |
| Cloud seeding | 2555 |
| Desalination | 265,823 |
| Dew harvesting | 100 |
| Agricultural drainage water | 20,129 |
| Fog harvesting | 949 |
| Fossil water | 855 |
| Greywater | 6534 |
| Iceberg towing | 70 |
| Rainwater harvesting | 8969 |
| Virtual water | 8485 |
| Wastewater treatment | 321,782 |
| Total count | 643,101 |

Based on PT, there were two change points (mutation #1 in 1984 and mutation #2 in 2008) in the number of UWR publications (Fig. 1). Accordingly, the studied period is divided into three sub-periods, pre-mutation #1 (1971–1983), mutation #1-#2 (1984–2007) and post-mutation #2 (2008–2019) encompassing 9874, 92,419 and 489,078 UWRs academic records, respectively. Which shows increasing concern and vitality on studying UWRs to address water scarcity through finding and exploiting new alternative water resources as UWR.

### 3.2. Bibliometric analysis of the literature

Fig. 2 shows the relevant terms and their network of co-occurrences elucidating the knowledge structure of UWRs research. VOSviewer recognizes the keywords as nodes connected to a cluster and a larger node size indicates a more frequently used term. The curves between the nodes demonstrate their co-occurrence. The distance between two nodes shows the co-occurrence and the colour indicates the strength of the co-occurrence. The red to blue spectrum signifies a higher to lower density weight of network-forming nodes.

In the current paper, three clusters were identified namely: *i*) Policy and management related keywords such as decision-making, water planning, water resources management, cost-benefit analysis, and sustainable development (grouped in the red cluster). *ii*) nonconventional water resources, water demand, water availability, and climate change (grouped in the green cluster), these show the clear nexus between climate change and UWRs as an adaptive management approach to reducing the misbalance between water supply and water demand. *iii*) desalination, virtual water, surface water resources, and arid regions (grouped in the blue cluster). The presence of the term ‘arid regions’ in this last cluster indicates more focus on desalination and virtual water as UWRs to eliminate water scarcity in arid and semi-arid regions. The most prominent keywords related to UWRs are desalination, wastewater treatment, and water supply.

### 3.3. Maps with locations of UWRs utilizations

Distribution maps with marked locations in fog, dew, rainwater harvested, and cloud seeding projects as Atmospheric Unconventional Water (AUW) and artificial recharge, fossil water as Unconventional Ground Water (UGW) and, iceberg water and virtual water projects as Transferred Unconventional Water (TUW) are shown in Fig. 3. AUW, TUW, and UGW produce drinking water and supply water required for agricultural use, especially in arid, semi-arid or seasonally arid regions of the world.

Based on Fig. 3, the most favourable location for fog and dew water harvesting depends on variables such as climatic and meteorological conditions, and a mountainous or coastal area (Gido et al., 2016); for example, in South America, sections of the coastal areas of the Pacific Ocean which receive only very small amounts of annual rainfall. Stratus clouds as low-level clouds frequently form over the cold ocean water and move inland, which lead to foggy areas on the coastal zones with virtually no precipitation. In these coastal areas, fog water harvesting projects intend to provide fresh water for the local people and support agricultural and reforestation activities.

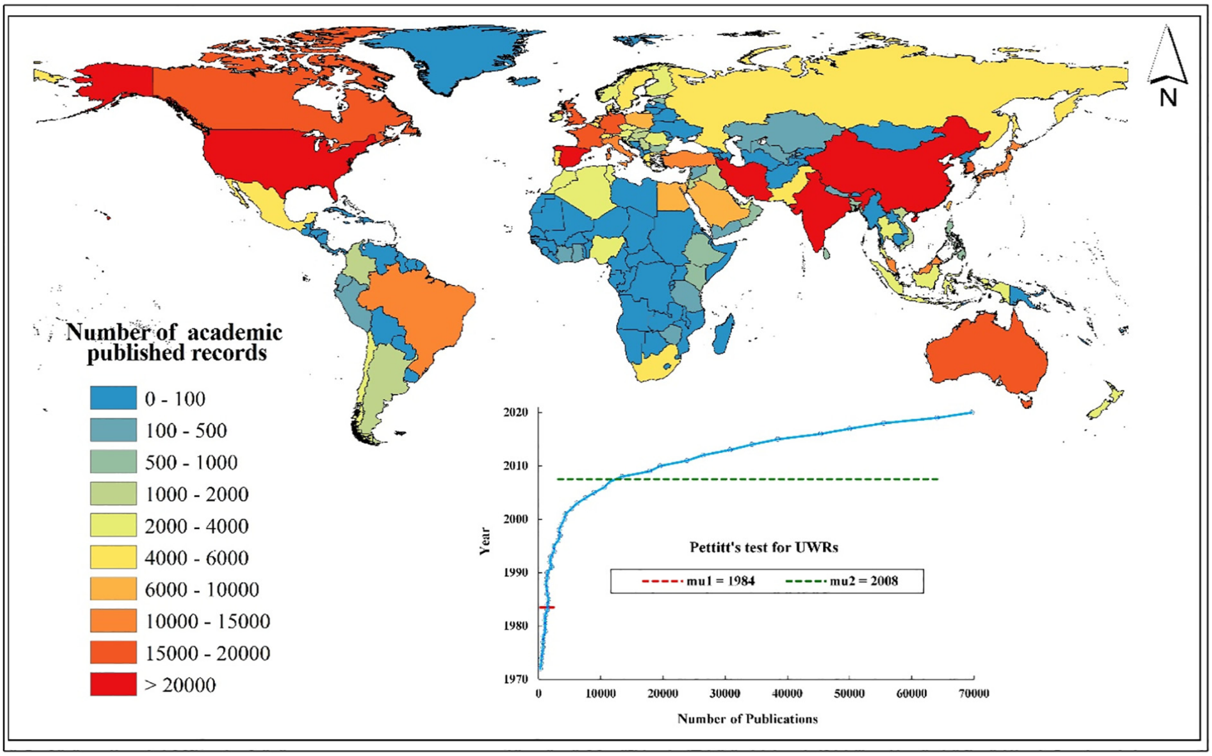

**Fig. 1.** The global distribution of published academic records on UWRs and Pettit's test.

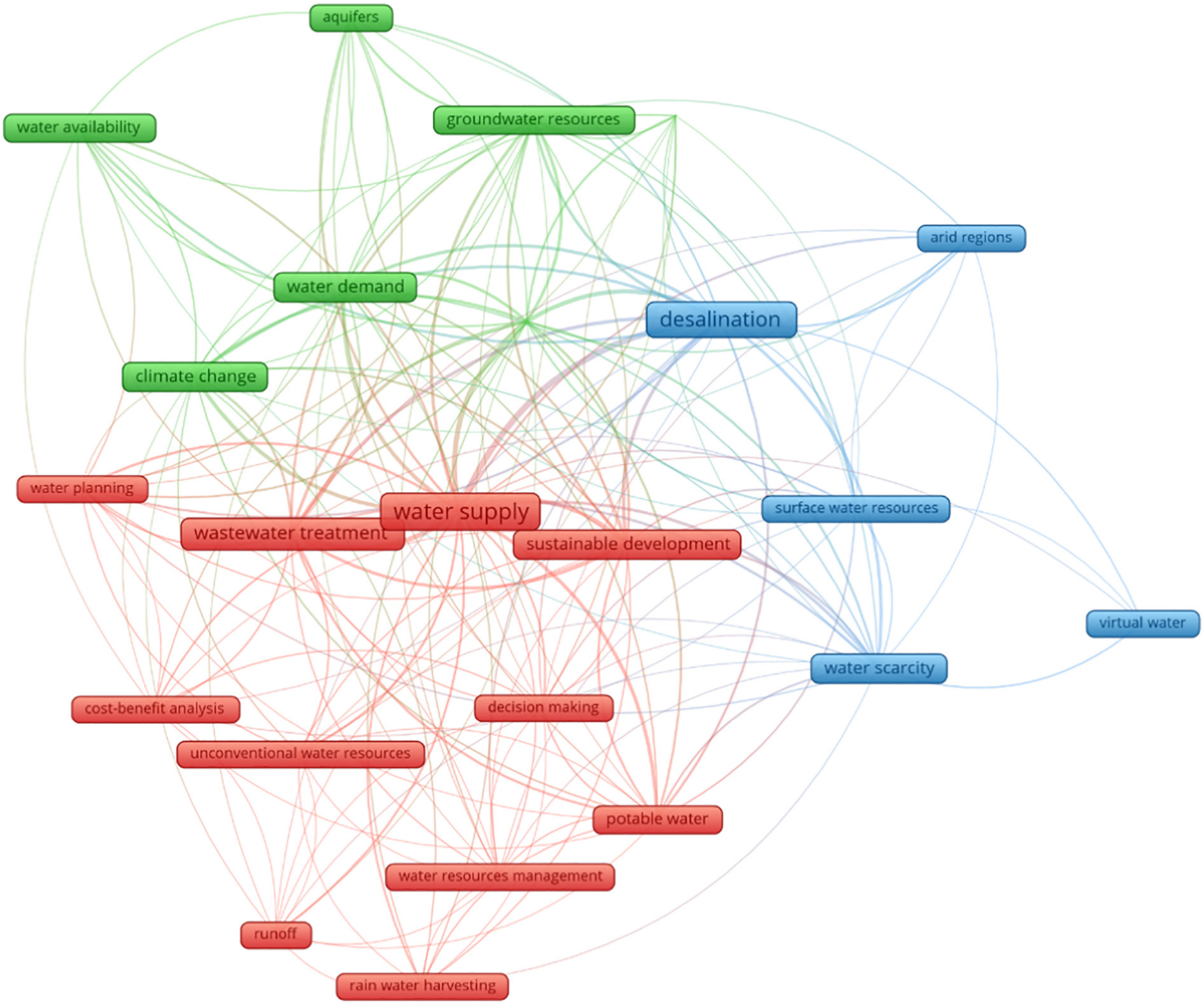

**Fig. 2.** High-frequency keyword network visualization map indicating the most prominent keywords related to UWRs.

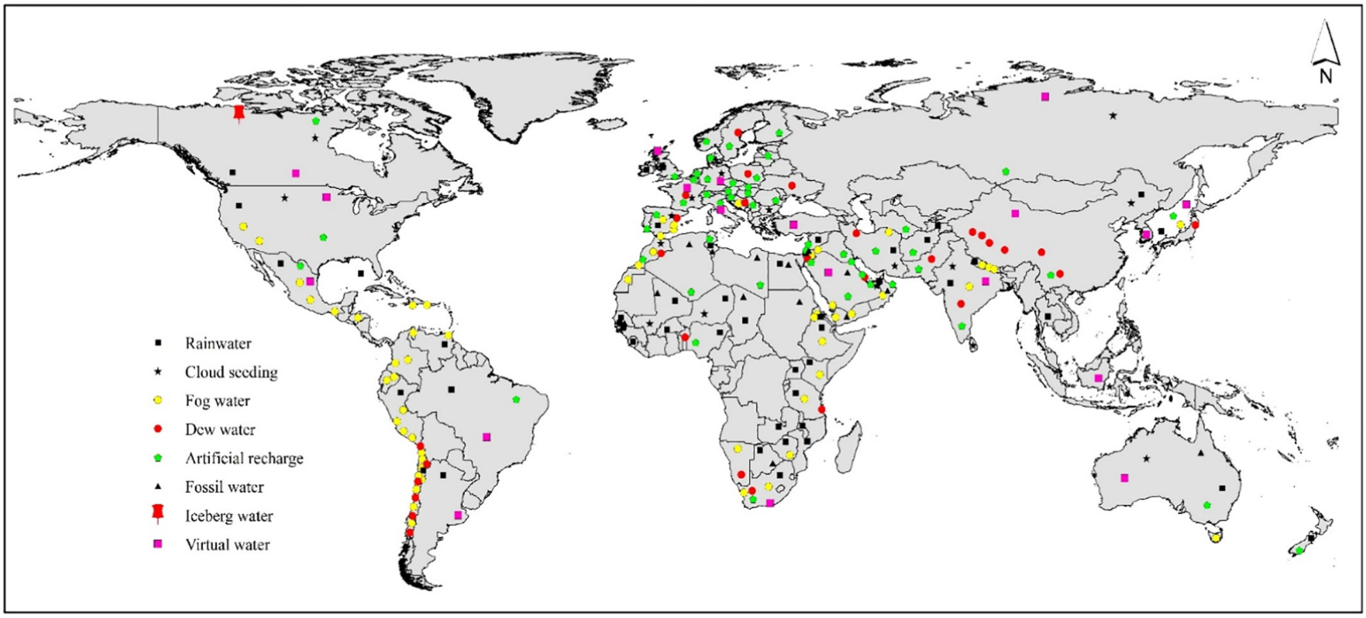

**Fig. 3.** Map with locations marked for artificial recharge, fossil water, iceberg melted water utilization, virtual water, fog water harvesting, dew water harvesting, rainwater harvesting and cloud seeding (extracted from the literature review presented in Table 2 and Appendix B).

In humid areas, due to the frequency of rainfall events, dew is not very important and is ignored, but in arid areas and desert environments such as the Middle East and African countries, dew is a precious gift to both plants and small organisms (Sharan, 2006). As shown in Fig. 3, the most fog water projects were conducted in South Africa, Chile, the USA, Yemen, Peru, Iran, and Australia, and the most dew water projects were conducted in Chile, Spain, Japan, Sweden, and India.

In the arid and semi-arid regions of the world, an extreme lack of conventional water and low precipitation lead to the utilization of rainwater harvesting (RWH) (Iraq, India Syria, China South Africa, and Tunisia). Even some water-abundant countries have introduced RWH systems. Germany has been developing RWH practical projects since the 1980s and has implemented research to evaluate the practicality and feasibility of runoff collection (Nolde, 2007; Ammar et al., 2016; Ali et al., 2020; Gebru et al., 2021).

The biggest cloud seeding project was carried out in China to increase the amount of precipitation over several arid regions where rain is needed. Also, cloud seeding projects have been carried out in the United Arab Emirates, Iran, India, and the USA. For example, in India, the State Government of Karnataka has carried out a cloud seeding program during the period from 21 August to 07 November 2017 (Khalili et al., 2008; Zoljoodi and Didevarasl, 2013; Chien et al., 2017; Kulkarni et al., 2019; Kumar and Suzuki, 2019).

Different types of recharge aquifer structures are widely used and applied at different scales and for different reasons in countries worldwide. Many countries located in the Middle East have arid and semi-arid climates with severe water scarcity, as well as other regional characteristics such as economic, social, demographic, cultural, environmental, political, or developmental problems, leading the development of aquifer recharge structures (Fig. 3) and the extraction of non-renewable fossil water (Haddadin, 2002; Rahman et al., 2012; Malekmohammadi et al., 2012). Sprenger et al. (2017) have pointed out that 224 artificial recharge sites are currently located in 23 European countries (e.g., Slovakia, Hungary, Poland, Germany, Switzerland, France, and Finland) which produce large quantities of drinking water. As shown in Fig. 3, most fossil water projects were conducted in Algeria, Libya, Niger, Chad, Yemen, Egypt, and Australia. The largest known fossil water aquifer in the world, the Nubian Sandstone Aquifer System (NSAS), is in North and North-eastern Africa, covering two million km$^2$ under the nations of Egypt, Libya, Chad, and Sudan. Also, in the northern region of the Kalahari, in central southern Africa (South Africa and Namibia), a deep aquifer in cave stone was found that seemed to be confined with little to no leakage for long periods (Mazor et al., 1977; De Vries et al., 2000).

Based on the literature review, in the cold climates of Newfoundland, in Canada, the local people were encouraged to use iceberg water due to the availability of this water resource as a legacy from their ancestors (Spandonide, 2009).

According to Deng et al. (2021) for virtual water trades (traded volume) between major countries, all imports and exports of virtual water were considered (Fig. 3). Based on the imported trade water data among major countries, the growth rate of China's virtual water is the largest (due to the huge imports of agricultural products) followed by Argentina, Saudi Arabia, and Brazil. Russia had the largest growth rate in exported virtual water. The highest contribution of traded water as exported virtual water was conducted by Australia, India, and Indonesia.

Fig. 4 shows the distribution maps of Processed Unconventional Water (PUW), including wastewater, desalinated water, and agricultural drainage water. The growing competition between industrial and domestic sectors for limited freshwater resources has motivated investment in wastewater and greywater treatment[1] (Oron et al., 2014) in many countries around the world, such as North America, north and southwest Europe (Spain, Italy, and France), Australia, China, and South Africa. Technical solutions and public policies in developed countries support the treatment and use of wastewater, but the situation is not the same in developing countries that struggle with inadequate treatment facilities, leading to agricultural irrigation using untreated wastewater (Sato et al., 2013; Qadir et al., 2020). It is worth mentioning that greywater treatment has already been conducted in many countries around the world and is becoming increasingly commonplace in water-stressed areas such as Australia, China, India, Algeria, the Middle East, and Mediterranean countries (Shaikh and Ahammed, 2020).

Desalination can be found in many places around the world, and it is becoming a main alternative water supply source in the many Mediterranean and Middle East countries where natural water resources are restricted and availability of seawater is viable to satisfy the increasing demands for sustainable development (Tsiourtis, 2008; Nair and Kumar, 2013). Fig. 4 shows that utilizing agricultural drainage water has been piloted in many countries around the world, especially in India, Egypt, Syria, Kazakhstan, and Uzbekistan.

## 4. Discussion

The literature review showed that an immense number of peer-reviewed journal articles has been published on UWRs in the past few decades, demonstrating the importance of this field. The drastic increase in the production of science on this topic since 2010 also highlights the increasing awareness of these technologies. And while the USA and China are record-holders in publishing on this topic, other countries, such as India, Iran and Spain, have developed a clear interest here; one reason for this being that these countries are also particularly affected by water scarcity. In addition, UWRs offer important opportunities for synergies between water scarcity adaptation and mitigation. Using UWRs is essential to meet the challenge of increasing water demands at a time when the severe changing climate as a result of global warming is forcing fluctuations to the water cycle and having important effects on the availability of water resources. Also, utilizing UWRs is vital to achieve the Sustainable Development Goals (SDGs). In recent years, more countries have focused on sustainability aims related to water, including UWRs, reuse of water, sustainable water use in agriculture and clean water production in part due to global, supranational and national agendas and policies (Djuma et al., 2016; Aznar-Sánchez et al., 2018).

The bibliometric analysis extracted through the VOSviewer resulted in three large clusters, namely: (1) unconventional water resources, water supply, water planning and management, (2) water availability, water demand, groundwater/aquifer and climate change (3) water scarcity, arid regions, surface water, desalination and virtual water which strongly shows the importance of considering water planning in the utilization of UWRs worldwide.

The grouping of the UWRs into four categories proved to be useful when comparing UWRs of a similar 'origin'. The UWRs were categorized as: *i*) Atmospheric Unconventional Water (AUW) resources, including fog water, dew water, cloud seeded water, and rainwater. *ii*) Processed Unconventional Water (PUW) resources, including desalinated water, wastewater treated, greywater treated, and agricultural drainage water. *iii*) Transferred Unconventional Water (TUW) resources, including iceberg towed water and virtual water. *iv*) Unconventional Ground Water (UGW) including artificial recharge and fossil water.

Mapping of UWR studies demonstrated that (a) some UWRs have clear geographic limitations, (b) some UWRs overlap in their geographic distribution, (c) some are practiced only in certain contexts, and (d) some UWRs are negligible in their abundance/implementation. For example, fog and/or dew harvesting, iceberg or fossil water, and desalinization can only occur where the proper geographic conditions are present. Fog and dew harvesting overlap in the Pacific Coast of South America, Southern Africa, and parts of Southeast Asia; rainwater harvesting overlaps with fog harvesting for most of Africa; and cloud seeding, and dew harvesting are both practiced in the Middle East. Managed Artificial Recharge, cloud seeding, and wastewater use demand certain legislative frameworks since their unskilled implementation

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[1] Greywater has been included in the wastewater category because it is hard to separate from wastewater.

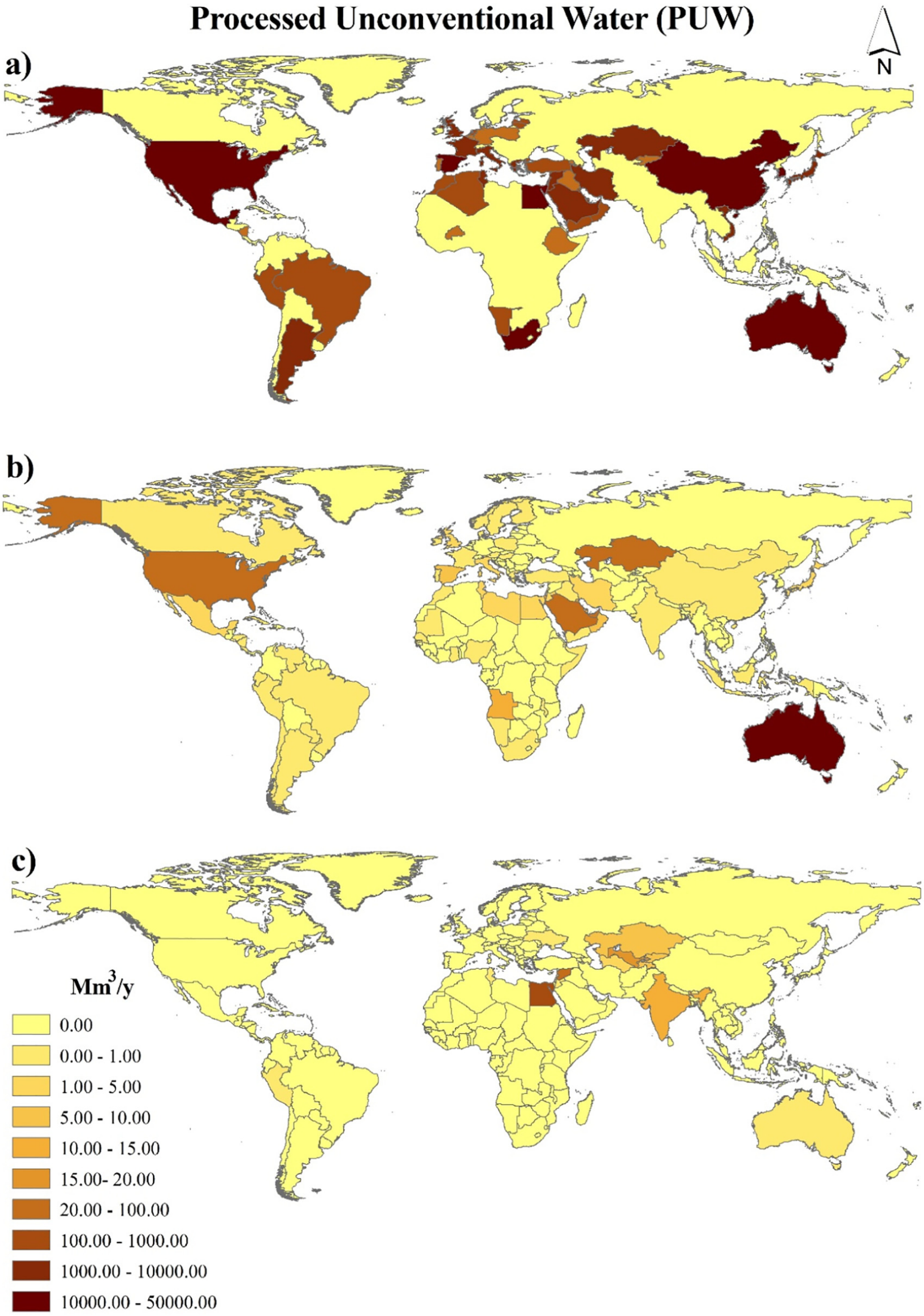

**Fig. 4.** Map with locations marked for a) used treated wastewater, b) desalination water, and c) agricultural drainage water utilization extracted from literature review presented in Table 2 and Appendix B.

may cause significant harm to the environment, both regionally and across borders. Agricultural drainage water utilization, as well as fog or dew harvesting, iceberg water use, and cloud seeding are so far minor water providers and are mostly only used in unusual or climatically extreme conditions. The global maps therefore show the opportunities as well as the limitations that UWRs bring about.

### 4.1. Cost/benefit analysis

UWRs that can alleviate water stress, especially in arid and semi-arid regions, have many challenges and side effects. None of the UWRs mentioned are accessible worldwide, and most of them are restricted to specific locations. Some key points need to be considered, such as the existence of the kind of UWR, cost, acceptability, political agendas, supportive plans for empowering local people to access safe potable water in remote areas. To select the best alternative, it is difficult to compare the costs of UWRs utilizations globally, due to variations in the materials and labour costs, maintenance, additional resource costs, presence or absence of subsidies, and efficiency of UWRs systems in a given location (Qadir et al., 2018; Hussain et al., 2019). Costs associated with UWR utilization are also condition dependent; for example, in desalination procedures, cost depends on many factors including the desalination method, the level of feed water salinity, the energy source, the capacity of the desalting plant, and other site related factors. The UAE struggles to find new water resources other than desalinated water, due to its rapid population growth. It was successful in enhancing rainfall through cloud seeding, which was found to be more cost-effective than the desalination method (Hussain et al., 2019). However, in the last few years, due to much lower energy consumption and the recent advances that have been achieved in membrane technology, reverse osmosis among all the existing methods is the optimal and desired choice (Karagiannis and Soldatos, 2008). In another example, the cost of rainwater harvesting (RWH) depends on the scale at which RWH is done, e.g., at a single-house scale, the cost of rainwater is about $\$4.7\ \mathrm{m}^{-3}$, while on an apartment building scale, it is much lower at approximately $\$1.65\ \mathrm{m}^{-3}$ (Morales-Pinzón et al., 2015). Therefore, it is difficult to precisely quantify the costs of the different forms of UWRs globally, but some positive and negative aspects of UWRs can be gathered. In Table 4, a summary of the advantages and disadvantages of UWRs is presented.

### *4.2. Possible solutions to overcome limitations of UWRs utilization*

Even though utilizing UWRs would benefit from enhancing water resources in water scarce areas some major obstacles in utilizing UWRs remain. To overcome these obstacles and limitations, some solutions are presented. For instance, to facilitate fog water and dew water harvesting and boost the acceptance rate of these kinds of water resources, involving local people of both genders and asking local and international volunteers could effectively tackle those difficulties. As weather modification such as cloud seeding could have long-term effects on weather patterns and the hydrological cycle, clear international water rules and legislations are needed with conditions agreeing to share the profits of the transformed rainfall

**Table 4**
A summary of the advantages and disadvantages of UWRs (See the references in Appendix C).

| UWRs | Advantages | Disadvantages |
|---|---|---|
| Artificial recharge water | 1) Cost-effective<br>2) Has the potential for use in flood control<br>3) Boosts water quality using natural filters<br>4) Does not require complex technology | 1) Needs regular maintenance<br>2) Can cause reduced stream flow in arid environment<br>3) May disturb soil and vegetation cover |
| Agricultural drainage water | 1) Can be reused and act as a valuable supplement in the face of scarcity | 1) One of the major causes of groundwater and surface water pollution |
| Cloud seeded water | 1) Increases precipitation and makes land more usable<br>2) Helps to regulate weather patterns in specific locations<br>3) Improves economy through increasing crop quality and quantity<br>4) Decreases the impact of drought events | 1) Needs specific atmospheric conditions and capable clouds<br>2) Is expensive and cannot be used everywhere<br>3) Its efficiency is still under review; It is not always a reliable method<br>4) Changes weather patterns in other areas and causes weather-related disasters |
| Desalinated water | 1) Due to the sheer volume of seas and oceans all over the world, it is an accessible water resource everywhere | 1) Disposing of the salt created can be hard and damaging to the environment<br>2) The cost of desalination is not affordable for developing countries and it can only be used in rich countries encountering a lack of water, such as countries in the Middle East<br>3) Desalination requires a continuous input of energy, chemicals, and labour (high energy consumption) |
| Dew water | 1) Is energy-free<br>2) Does not require sophisticated instruments<br>3) Does not need processing or treatment before use<br>4) Requires low investment and maintenance | 1) Is not available everywhere<br>2) Needs regular maintenances and supervision by experts<br>3) Has a small yield |
| Fog water | 1) Does not rely on energy consumption<br>2) Needs green technology<br>3) Very low-cost collection system<br>4) Good-quality freshwater<br>6) Requires very little maintenance or additional equipment<br>7) Does not need processing or treatment before use | 1) Seasonal fluctuations in the occurrence and intensity of fog in a calendar year limits availability<br>2) Can increase car accidents in fog prone areas<br>3) Is not accessible all over the world<br>4) Needs regular supervision from experts<br>5) Volume of the harvested water is not considerable |
| Fossil water | 1) Provides good quality water<br>2) Has Large resources available | 1) Has high costs in terms of drilling and pipelines<br>2) Is unrenewable |
| Greywater | 1) Is useful for landscape irrigation in urban areas<br>2) Provides plant nutrients and fertilizers in agriculture | 1) Spreads infectious diseases and causes bioaccumulation of toxic elements in plants<br>2) Increases salinity and nitrogen in the soil<br>3) May cause groundwater contamination |
| Rainwater | 1) Can be done using a number of different building materials based on the budget<br>2) Is easy to use for local people<br>3) Produces a sufficient quality of harvested water<br>4) Is renewable and environmentally friendly<br>5) Is useful for household consumptions | 1) May produce harvested water affected by air pollution or other kinds of impurities<br>2) Is sensitive to drought events<br>3) May differ seasonally and not always be available |
| Iceberg water towed | 1) Is a pure water resource<br>2) Creates new jobs<br>3) Prevents icebergs damage to offshore structures through iceberg transferring | 1) Has a major issue with the difficulty of the transportation of large icebergs over open seas<br>2) Influences design structures in the offshore area<br>3) May disturb both shallow and deep polar seafloor habitats<br>4) Is not cost-efficient |
| Virtual water | 1) Is suitable for arid countries through importing goods to avoid using local water sources<br>2) Is the easiest way to achieve peaceful solutions to water conflicts<br>3) Saves local water resources<br>4) Prevents competition over water | 1) Is difficult to quantify the exact amount of virtual water used<br>2) Does not have any kind pf pricing protocol in IWRM<br>3) Causes unfair competition between countries through unequal water resource distribution |
| Wastewater | 1) Is suitable for agricultural and urban landscape irrigation, dust control, toilet flushing, and use in carwashes | 1) May be dangerous to aquatic life<br>2) Requires sophisticated treatment<br>3) Requires the continuous input of energy, chemicals, and labour. |

patterns. As RWH has uncertainty due to climate oscillation and weather fluctuation, long term studies on climate and weather conditions before establishing RWH structures may help provision a stable water source. Desalination is technically highly and necessitates significant innovation to be affordable and efficient. To motivate water reuse, new regulations and incentives could be employed such as establishing a quota for the amount of treated wastewater use, designing improved technical treatment systems at lower costs to promote water reuse and making this a unique possibility on water markets. Water authorities may want to validate water reuse and expand their diversity of usages. In general, UWRs could become more widely used by modifying policies around water, employing more sophisticated, innovative, cost-effective, and environmentally friendly techniques, and increasing awareness about UWRs and their acceptability.

### *4.3. Closing the water supply-demand gap*

UWRs are an opportunity towards water security. Global water demand for agriculture, energy production, industrial use and human consumption is around 4600 km$^3$/year (Boretti and Rosa, 2019; Piesse, 2020). The total global water withdrawal considering conventional water resources and unconventional water resources including treated wastewater, agricultural drainage water, fossil water and desalinated water is about 4011km$^3$/year based on the latest statistics extracted from Aquastat (Fao, AQUASTAT, 2021). The total global freshwater withdrawal, which can be considered as used conventional water resources is approximately 3756 km$^3$/year (Fao, AQUASTAT, 2021). Currently 255 km$^3$/year UWRs is used worldwide, of which 131 (51.37%), 83 (32.54%), 35 (13.72%), 5.95 (2.35%) km$^3$/year belongs to agricultural drainage water, fossil water, desalinated water, and treated wastewater, respectively (Fao, AQUASTAT, 2021). For other types of UWRs, the annual potential (or actual) usage is difficult to estimate and there is no exact amount for annual usages. However, the existing estimations of some UWRs, such as atmospheric water (fog, dew and rainwater harvesting, cloud seeding), icebergs are presented in Table 5.

Among sources of UWRs, the greatest volume belongs to seawater, with 1.35 billion km$^3$. Currently 35 km$^3$/year is produced as desalinated water, followed by Antarctic ice, which produces 27 million km$^3$ of freshwater and, annually, 2000 km$^3$/year of icebergs break off, giving the potential to be utilized in the future (Lewis, 2015; UN-Water, 2020). Fossil water with 25 million km$^3$ is the next largest source of UWR, with optimistic estimations suggesting there is 30 million km$^3$ deep groundwater, 5 million km$^3$ of which is considered renewable and approximately 25 million km$^3$ is non-renewable or fossil water, which of it approximately 83 km$^3$/year is being used (UN-Water, 2020). Whereas most of UWRs present renewable water resources, fossil water is considered a non-renewable form of groundwater extraction which is not sustainable and may provide a false sense of short-term water security. Atmospheric moisture contains 13,000 km$^3$ of water as the feed of cloud seeding, fog and dew water, which may diminish local water scarcity in areas with limited reliable rainfall and water (Shan et al., 2020). Fog and dew water yield depends on the intensity, duration, and frequency of the events, and daily fog water yields range from 2 to 20 L/m$^2$ of fog water collection mesh (Correggiari et al., 2017). Dew has a theoretical maximum daily water yield of 0.8 L/m$^2$ (Monteith and Unsworth, 2013) and is a more common occurrence globally than fog (Jacobs et al., 2002; Vuollekoski et al., 2014). Due to the low yield of dew and fog, it is unlikely that fog and dew harvesting will replace conventional water resources and should thus be viewed as supplementary resources, especially during the driest periods of the year (Kaseke and Wang, 2018). Annual generated wastewater and greywater is 380 km$^3$/year (UN-Water, 2020); of this 5.95 km$^3$/year is treated wastewater (data used in this study covers all treated wastewater in every sector which encompasses domestic, commercial, and industrial effluents, storm water, and runoff) which is used directly for irrigation and 8.35 km$^3$/year is untreated municipal wastewater used for irrigation purposes (Graham et al., 2010; Baggio et al., 2021). The annual usage of agricultural drainage water which is used directly is around 131 km$^3$/year (Fao, AQUASTAT, 2021).

**Table 5**
The volume feed of UWRs.

| UWRs | Total volume | Reference |
|---|---|---|
| Sea and oceans[a] | 1.35 billion km$^3$ | Baggio et al. (2021) |
| Wastewater and greywater[b] | 380 km$^3$/year | Qadir et al. (2020) |
| Atmospheric water harvesting[c] | 13,000 km$^3$ | Graham et al. (2010); Shan et al. (2020) |
| Antarctic ice[d] | 27 million km$^3$ | UN-Water (2020) |
| Fossil water[e] | 25 million km$^3$ | Foster and Loucks (2006); Gleeson et al. (2016); Ferguson et al. (2018) |

[a] Sea and oceans.
[b] All the produced wastewater around the world.
[c] Atmospheric water vapor.
[d] Iceberg.
[e] Unrenewable groundwater.

While the potential use may be large, economic, social, environmental, and political challenges prevail. As such, fog and dew water harvesting need to consider the regional and transboundary impacts and environmental aspects, and iceberg towing through seas/oceans and cloud seeding may need to consider issues with the technology and facilities needed. Also, desalinated water may be perceived as a competitor to UWRs such as iceberg water because the relevant technologies are much better developed, and they are already in use in many areas of the world (Smakhtin et al., 2001). Thus, utilizations of UWRs are accompanied by controversial questions of which methods to consider at the international, regional, or domestic scales.

Among the atmospheric unconventional water resources, fog and dew alternatives give a small volume of water in comparison to rainwater harvesting and cloud seeding. Mountainous and coastal regions are among the best site selection for effective fog and dew water collection (Dodson and Bargach, 2015). Although cloud seeding gives a considerable volume of water, it needs specific atmospheric conditions with capable clouds and needs sophisticated technologies. The main advantage of these atmospheric UWRs is that they produce renewable clean water sources with low-to-no pre-treatment. However, the seasonality (availability of atmospheric UWRs at different times/seasons of the year) is the main disadvantage of atmospheric UWRs.

Although all processed UWRs, such as desalination, are categorized as renewable sources and give a huge volume of water, they can cause environmental damage, and need sophisticated treatment with high energy consumption. Currently, more than 150 countries use desalination to supply potable water for 300 million people (Mickley, 2018). Approximately 24.85 billion m$^3$ annually of global desalination capacity is in high income countries and only 0.035 billion m$^3$ annually is produced in low-income countries. Almost 15.4 billion m$^3$ of the desalination capacity is in the Middle East, China, the United States, and Latin America (Jones et al., 2019; UN-Water, 2020).

Among unconventional ground water UGWs, fossil water is not renewable, However, artificial recharge has been considered as renewable source but may cause environmental damage. Although iceberg water as transferred unconventional water, gives a pure water source for supplying freshwater, the transportation of large icebergs over open seas is expensive.

As the literature has pointed out, recovering a volume of unconventional water from different resources (such as fossil water, atmospheric water, Arctic and Antarctic ice, and seawater) can ease water stress around the world. However, some UWRs, such as cloud seeding and iceberg towing, are difficult to assess due to the lack of information and facilities, hence they remain in their infancy until further development (Walker, 2016). Today, among all forms of UWR, desalinated and treated wastewater produce the greatest amount of water. Approximately 97% of the planet's water resources, delivers unlimited raw material for seawater desalination (UN-Water, 2020). The key to the long-term sustainability of desalination is the management of the brine produced, both environmentally and economically. Desalinated water provides a climate independent and steady supply of good-quality water (Elsaid et al., 2020). However, fog and dew water provide small yields but, surprisingly, deliver precious support to local communities to address water scarcities (Hussain et al., 2019).

## 5. Conclusion

The findings of this study reveal that different forms of UWRs are used in specific regions of the world, with water scarce areas featuring prominently. UWR implementation at a regional and local scale is influenced by technical aspects, climate, and socio-economic conditions. This study also showed that truly assessing the potential of closing the water gap is currently numerically difficult, as data only exists in the form of singular case studies. Therefore, future work on UWRs should focus on:

- Encouraging international collaboration in collecting, storing, and analysing numerical data and information on the implementation and performance of UWRs.
- Developing and applying integrated numerical modeling on the physical and socio-economic potential of UWR implementation and the discovery of hotspot applications.
- Motivating water resource management agencies and policymakers to support scientific funding for UWRs studies and develop supportive practical plans in UWR utilization.

## CRediT authorship contribution statement

**Zahra Karimidastenaei, Ali Torabi Haghighi, and Tamara Avellán**: Conceptualization, methodology; **Zahra Karimidastenaei, Ali Torabi Haghighi**: Software; **Zahra Karimidastenaei, Ali Torabi Haghighi and Tamara Avellán**: Data curation, writing-original draft preparation. **Zahra Karimidastenaei, Ali Torabi Haghighi and Tamara Avellán**: Visualization, investigation. **Ali Torabi Haghighi, Tamara Avellán, Mojtaba Sadegh and Bjørn Kløve**: Supervision; **Zahra Karimidastenaei, Ali Torabi Haghighi, Tamara Avellán, Mojtaba Sadegh and Bjørn Kløve**: Reviewing and editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.154429.

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