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Water scarcity: A global hindrance to sustainable development and agricultural production – A critical review of the impacts and adaptation strategies

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Abstract

Water is essential for sustaining life and required for carrying out basic daily activities. Even though water covers the vast majority of the earth's surface, the availability of fresh water, which is necessary to maintain human activities, is limited, making it a scarce resource. Climate change, overexploitation of groundwater, and population growth are all putting significant pressure on natural water sources, which pose a serious threat to various sectors of society, especially in agriculture. Future projections of freshwater availability indicate agriculture production will suffer a significant shock globally, including in India, leading to a threat to food security and sustainability. To ensure the sustainability of this vital resource, it is crucial to use water sensibly. Moreover, it is essential to adopt certain strategies to manage agricultural water use effectively. This includes adopting various water-efficient techniques such as 'micro-irrigation', 'irrigation scheduling', 'conservation agriculture', 'crop switching' and so on. In this review, firstly, we discuss water scarcity and its types, causes, crisis for water shortages and hindrance to sustainable development from a global perspective emphasizing the Indian scenario as a developing nation. Secondly, we elaborated our discussion on water scarcity in agriculture including the impacts of water scarcity on agricultural production and its connection to climate change, population growth, and overexploitation of natural resources globally focusing on the Indian scenario. In addition, innovative water management practices and adaptation strategies to manage agricultural water use, constraints, and the need for further research are also covered. It is anticipated that this review will benefit researchers and policymakers by providing useful information on the impacts of water limitation and adoption strategies.

Impact statement

One of the biggest problems we have today is water scarcity. Our current and future farm productivity and food and nutritional securities are heavily reliant on water. However, the primary obstacle to sustainable development nowadays is the growing shortage of water. Water shortage is a prevalent issue, even in nations with sufficient supplies of water (Mishra 2023). Climate change leading to global warming and other associated concerns is expected to result in rising temperatures and precipitation deficit making water scarcity worse in the near future (Alotaibi et al. 2023). A growing number of severe and regular droughts are affecting agricultural productivity. In addition, the world's population will continue to rise, as will their levels of living, and as dietary preferences and the consequences of climate change deepen, making this problem alarming. The agricultural industry is one of the leading sectors responsible for water shortage. Nearly 70% of water withdrawals come from farming, and in certain developing nations, it goes up to 95% (Ingrao et al. 2023). As time goes on, we will need to use water resources more responsibly. If present water consumption trends continue, evidence points to the possibility that by 2025, two-thirds of the world's population may reside in water-stressed nations (du Plessis 2019). We must act now if we want to evidence a 'ZeroHunger world by 2030' set up by the United Nations. Hence, there is of pressing need to alleviate this scarcity by adopting

measures, capturing and reusing our freshwater resources, using wastewater more safely and raising agricultural production in addition to increasing water efficiency. While taking these actions would not stop climate change and associated issues like global warming, drought and so on from happening, it can lessen the likelihood that will cause hunger and other socioeconomic problems and may provide viable solutions to prevent them.

Introduction

Human civilizations have always relied heavily on water for its growth and development. Nonetheless, the growth of agriculture and the economy in recent years has made the shortage of water severe and raised political and social unrest, underscoring the necessity of resource allocation and sustainable development. In the twenty-first century, almost 25% of the world's population will have to deal with the issue of water scarcity (Alotaibi et al. 2023; Seckler 1999). Water scarcity is largely caused by urbanization and internal migration which tend to concentrate in industrialized centers (Basu and Shaw 2014; Oki and Quiocho 2020). A study reports that 933 million (32.5%) of the world's urban population resided in water-scarce regions in 2016, with 359 million (He et al. 2021). More than 2.4 billion people have lived in water-scarce countries since 2000, and by 2025, that figure is predicted to increase to 4.8 billion (Ayt Ougougdal et al. 2020). Water scarcity affects 40% of the world's population and is on the rise; every day, 1,000 children pass away from diseases linked to poor sanitation and water quality (Aversa et al. 2022). Water scarcity has been assessed globally using a variety of indicators that have been created since the late 1980s when it was acknowledged as a global issue (Liu et al. 2022). The most widely used indicator of water scarcity is the ratio of water supply to demand, commonly known as blue water scarcity (BWS) (Cai et al. 2017). Blue water is freshwater that can be used and can come from groundwater, lakes and streams. Truly, the world's biggest problem nowadays is a lack of blue/freshwater (Mancosu et al. 2015). Future food consumption is anticipated to rise, which will have a direct impact on the amount of water used for agriculture (United Nations Department of Economic and Social Affairs, Population Division 2013). Furthermore, considerable water usage for irrigation is anticipated in the context of growing competition between agriculture and other economic sectors due to increased water shortages and drought brought on by climate change (IPCC 2014). Since the processes of climate change are accelerating amid an atmosphere of uncertainty and financial instability, sustainable development has emerged as a major worry for modern society (Minenna and Aversa 2019). People are becoming more conscious of their impact on the environment and wildlife. Water and other basic materials should be used wisely, and this is becoming increasingly important.

In this paper, the authors portray a critical overview of water scarcity – its causes, impacts, present scenario, its relation to agriculture and possible adaptation strategies to mitigate the threat to sustainable development and agricultural food security globally and by emphasizing Indian perspectives. By offering useful information on the effects of water constraints in agriculture and adoption techniques, it is envisaged that this review will assist researchers and policymakers. Figure 1 showcases a pictorial overview of the various sources of water scarcity across the world and the remedial strategies through innovation and water-efficient agricultural practices and how they are linked with sustainability.

Water: An important economic resource – Supply and demand

Water can be considered an important economic resource that is heavily utilized by households, industries and agricultural farms for a variety of uses every day, such as drinking purposes, irrigation, generation of hydroelectricity, recreation and amenities. The quantity and quality of the available water have a crucial impact on these goods and services. Water management and distribution include considering its unique qualities as a resource (Turner et al. 2004). Water is a 'bulky' resource as it is abundantly available in nature. This indicates that it has a generally low economic worth per unit of weight or volume. As a result, unless a high marginal value can be produced, its transportation involves a high cost per unit of volume and is frequently not economically feasible across large distances. When compared to the little economic value achieved by using an

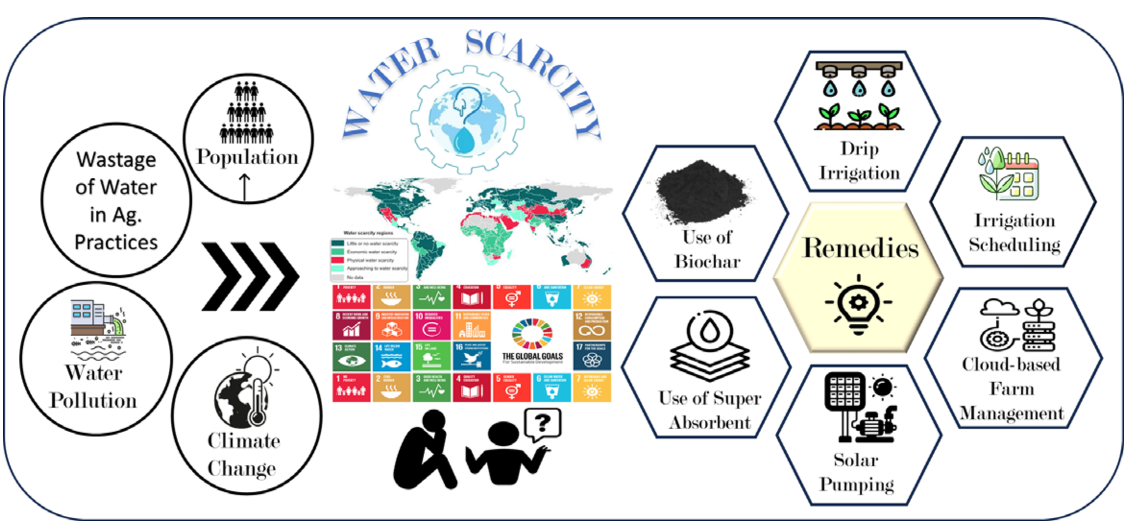

Figure 1. A pictorial overview of the various sources of water scarcity across the world and the remedial strategies through innovation and water-efficient agricultural practices and how they are linked with sustainable development goals.

additional unit of water, the expenses of abstraction, storage and any kind of transportation are often significant. This may result in the creation of location-specific water values.

Water also has additional characteristics in the sense that its supply cannot be easily predicted. It is governed by numerous processes, including water flow, surface evaporation and ground percolation. The interaction between groundwater systems and rivers/streams is crucial for maintaining ecological balance and water quality. Groundwater contributes to river flow, especially during dry periods, supporting aquatic habitats and ensuring a consistent water supply. This dynamic exchange regulates temperature, filters pollutants and sustains wetlands, essential for biodiversity (Sophocleous 2002; Winter et al. 1998). The supply of surface water is greatly influenced by weather variables and climate dynamics. As a result, the supply is unpredictable and inconsistent; 33% of the world's internationally shared river basins mostly in the developing countries of Africa and South Asia will be in either high or very high water stress categories by 2025 due to climate change (du Plessis 2019), industrial and agricultural growth as well a rise in population from 2.1 billion to 4.0 billion (expected) and the areas affected by 'severe water stress' will increase globally from 36.4 to 38.6 million km^2 (Alcamo et al. 2000). At first glance, there appears to be plenty of room to increase supply through appropriate technical work if just 15% or less of the available water is being consumed though the distribution of resources is uneven in both distance and time, making it impossible to fully realize the potential (Allan 1993). According to estimates, the rate at which groundwater storage is being depleted is between 100 and 200 km^3/year, which translates to 15–25% of total groundwater withdrawals (United Nations (UN) 2022). There are hotspots for groundwater depletion throughout the world, usually in regions where significant amounts of groundwater are drawn out for irrigation or to serve big cities. As a developing nation with a high population density, India witnesses a severe water-scarce scenario.

According to the 1991 and 2001 census data, India's per capita surface water availability is 2,300 and 1,900 m^3, respectively which are projected to drop by 1,400 and 1,190 m^3 by 2025 and 2050, respectively, based only on population projections and the presumption that water resources will remain available (Bhat 2014). Approximately, 680 km^3 of developed water resources are currently available (Saleth 2011). However, because of high costs, environmental issues, and interstate water problems, it is challenging to increase supplies beyond this point in a developing country like India. On the other hand, the Ministry of Water Resources (2000) projects that the total water demand will be between 784 and 843 km^3 by 2025 and between 973 and 1,180 km^3 by 2050, creating a demand–supply gap in water. By 2050, nine basins that account for more than four-fifths of India's total water use will experience physical water scarcity if the demand–supply imbalance widens (Amarasinghe 2007). Water demand will rise exponentially due to factors including population growth, rising incomes and urbanization, while supply will become more unpredictable and erratic making it more scarce and vulnerable.

Water scarcity: Types and causes

Water scarcity involves a range of conditions including water crisis and water stress. There are various degrees of water scarcity, such as, absolute or severe, chronic, seasonal, temporary, cyclical and life-threatening (Zisopoulou and Panagoulia 2021). To evaluate the degree, water scarcity is measured in terms of per capita annual water resources (AWRs) (Gosain et al. 2006). A region is 'water stressed' when the availability of water falls below 2000 m^3 AWR per person annually, as populations encounter significant challenges during droughts or artificial water shortages (Pereira et al. 2009). If the value of AWR per person falls between 1,000–1700 m^3 per capita, the region comes under 'regular water stress' (Food and Agriculture Organization (FAO) 2003). Numerous regions across the globe endure more acute situations with 500–1,000 m^3 or even less than 500 m^3 of water availability per person annually, which can be classified as 'chronic water shortage or water scarcity' and 'absolute or severe water scarcity', respectively (FAO 2003) (Figure 2). Numerous measures, including the Water Stress Index (WSI), Withdrawal-to-availability Ratio (WTA), Social WSI (SWSI), Water Poverty Index (WPI) and others, can be used to quantify water shortage (Damkjaer and Taylor 2017). Additionally, groundwater flow simulation codes like modular three-dimensional finite-difference ground-water flow model (MODFLOW) and contamination simulation codes such as a modular three-dimensional multi- species solute transport model (MT3DMS) and/or simulation of three-dimensional variable-density groundwater flow with multi-species solute and heat transport (SEAWAT) are essential for assessing the impacts of climate change on groundwater systems. These tools allow for quantitative and qualitative analysis, aiding in effective groundwater management. By simulating various scenarios, they help predict changes in groundwater levels and contamination spread, ensuring sustainable water resource planning (Harbaugh 2005; Langevin et al. 2008; Zheng and Wang 1999).

Types of water scarcity

According to Seckler et al. (1998), there are two primary forms of water scarcity: physical and economic.

Physical water scarcity

This is also known as 'absolute water scarcity', which usually occurs when water is unable to meet all demands (human and environmental flows) due to a fundamental absence of water (FAO 2020). Physical water shortage is typically observed in arid and semi-arid countries and is characterized by severe environmental degradation, diminishing groundwater and unbalanced water allocations (Giordano et al. 2019). As reported by the FAO of the UN (Food and Agriculture Organization 2020), 1.2 billion individuals reside in regions experiencing physical water scarcity (Figure 3). Farmers often necessitate new irrigation wells in these areas and submit applications for permissions. The competent authority evaluates if extracting water from the well could deplete the water levels of adjacent wells. Groundwater flow models, such as MODFLOW, an open-source model provided by the U.S. Geological Survey, have been employed to model and forecast groundwater flow and depletion rates for the past 30 years (Winston 2022). Furthermore, a newly developed MODFLOW framework, known as MODFLOW 6 has been introduced to accommodate numerous models within a single simulation (Hughes et al. 2017). Physical water scarcity is often seasonal and tends to grow dramatically due to rapid population growth along with climate change (Ingrao et al. 2023). Both blue and green components of water footprints are affected by physical water scarcity. In agricultural production, when a rainfall regime is unable to meet the crop's water requirements, green water scarcity (GWS) occurs (Rosa et al. 2020). Similarly, BWS is noticed when the water requirements for irrigation get restricted due to insufficient blue water (Ingrao et al. 2023). Food and energy

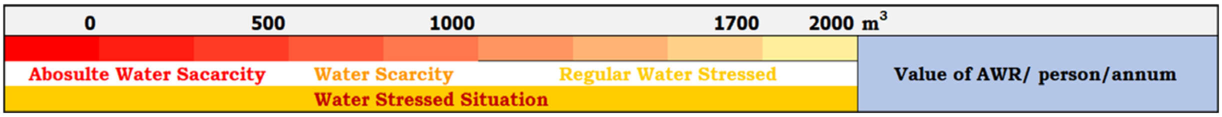

Figure 2. Various degrees of water scarcity based on per capita AWR availability.

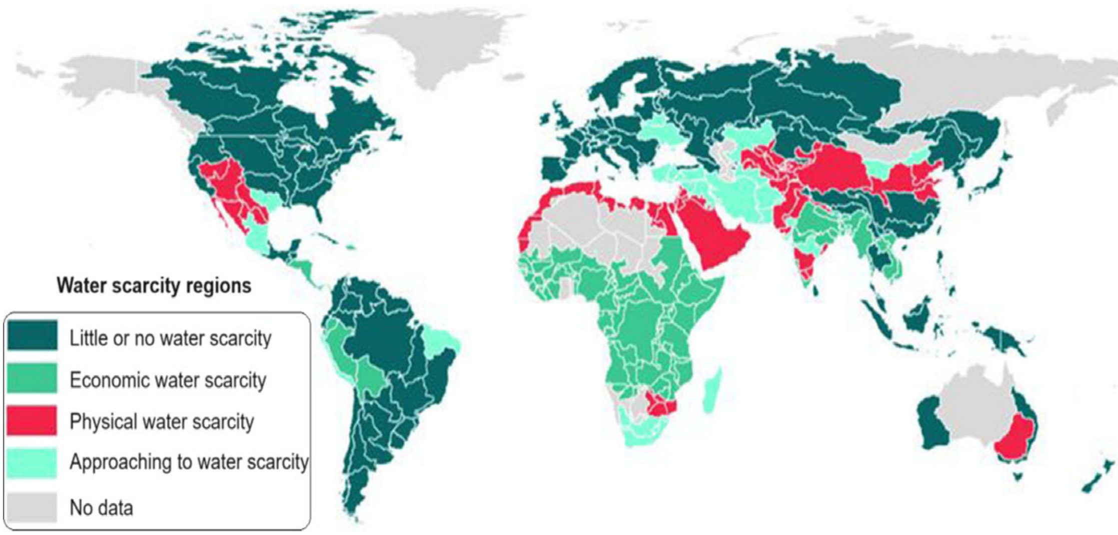

Figure 3. Water scarce regions in the world [data source: World Water Assessment Programme (2012)].

security are directly impacted by BWS, which is increasingly perceived as a global socio-environmental hazard (D'Odorico et al. 2020).

Economic water scarcity

Economic water scarcity (EWS) is the state in which there are physically abundant renewable blue water resources, but society's access to those resources is restricted due to a lack of institutional and financial resources (Molden 2013; Rijsberman 2006). An early definition of EWS identified nations with sufficient renewable water resources to fulfill present and future water demands, but which would require significant reforms to their water development strategies in order to fully utilize their freshwater resources (Seckler et al., 1999). EWS is caused either by inadequate infrastructure, which consists of storage, timely distribution and access to water (Ahopelto et al. 2019), or due to poor management of water resources that hinders access to abundant water resources (Bond et al. 2019). Regions witnessing EWS generally have adequate water resources to meet both human and ecological needs, but there is a limitation to access (Petruzzello 2023). As per the estimation of Food and Agriculture Organization (2020), over 1.6 billion individuals experience EWS (Figure 3). Underdevelopment and poor management can contaminate readily available water supplies or render them unfit for human consumption. This can also be the outcome of unregulated water utilization for industrial and agricultural systems, frequently at the expense of the general public. In addition, water use inefficiency is also the consequence of underestimating the economic value of water as a limited natural resource (Ingrao et al. 2023). The relationship between access and restriction and possession and dispossession of water resources is ultimately influenced by institutional, political and power dynamics, according to emerging research (Boelens et al. 2016; Huitema et al. 2009; Ostrom 2015). Therefore, the range of sociopolitical elements that interact at various scales must be taken into account to fully comprehend EWS. EWS can further be categorized as GWS, BWS, agricultural EWS and total water scarcity (TWS) (Figure 4). When crop production becomes stressed and irrigation is required to increase yields since green water or rainfall is not enough to support it, the ratio of irrigation water requirement to the total crop water requirement (CWR) is known as GWS (Rosa et al. 2018). BWS comes when there is not enough renewable blue water available and irrigation is not sustainable, the CWR cannot be met. In these situations, irrigation reduces freshwater supplies and affects environmental flows and the ratio of societal demand for blue water to the availability of renewable blue water is known as BWS (Vanham et al. 2018). Furthermore, a lack of BWS in the presence of GWS is known as an agricultural economic water shortage (Rosa et al., 2020). Moreover, when there is a lack of institutional or financial capacity together with GWS and BWS is known as TWS.

Causes of water scarcity

Although there are innumerable reasons for the severe water scarcity, which many nations of the world are facing nowadays, however, only a few major causes have been discussed in this paper.

Climate change and droughts

The variability of weather patterns due to climate changes and extremes has resulted in the occurrence of inadequate water availability, water scarcity and contaminated water supplies (UNICEF 2023). The probability of occurrence of severe droughts in numerous areas of the world is more likely as a result of climate change (Clarke et al. 2022). During droughts, as rainfall and precipitation

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Scarcity Level (cubic meter / year)											
0	10	20	30	40	50	60	70	80	90	100	110
Green Water Scarcity			Blue Water Scarcity				Agricultural Economic Water Scarcity				
Total Water Scarcity											

Figure 4. Various types of economic water scarcity including green and blue components of water resource availability. Data given in scarcity level is arbitrary. to provide an improved understanding and to distinguish between these scarcities more prominently.

decrease to a significant extent, soils and crops dry out easily and die, eventually. This has a significant influence on water levels in lakes and reservoirs when it happens over a long period in conjunction with heat wave events, leading to water scarcity for adjacent communities and cities (Lai 2022). Between 2001 and 2018, approximately 74% of natural disasters were related to water, such as floods and droughts. As climate change progresses, it is anticipated that the occurrence and severity of these events will escalate (UNICEF 2023).

Population growth

The world's demographical scenario has experienced a significant increase over the last century, and it is projected to continue rising by 2030 and 2050 (Foresight 2011). At present, the global population is expanding by approximately 83 million individuals each year (Islam and Karim 2020). Currently, a considerable fraction of the world's inhabitants, approximately 41%, reside in river basins experiencing water stress (UNESCO 2022). To feed this huge ever-growing population, food production must rise by 50% by the year 2030. Due to this augmentation in food production, water demand also needs to be increased by 40 to 50%, while municipal and industrial water requirements will escalate by 50 to 70% (UNESCO World Water Assessment Programme 2018).

Water pollution

Water pollution occurs when harmful substances contaminate water sources, such as rivers, streams, oceans and aquifers, making it unsafe for both humans and the environment (Denchak 2023). Pollution can originate from various sources, such as agricultural runoff carrying pesticides and fertilizers, untreated human wastewater and industrial wastes. Groundwater is also vulnerable to pollution, with various pollutants seeping into underground aquifers. The consequences of contamination can be immediate, such as when harmful bacteria from human waste pollute water, or can accumulate over time, such as the long-term effects of toxic substances from industrial processes on the environment and the food chain (Akpor and Muchie 2011).

Agricultural practices

According to the World Economic Forum (2015), the agricultural sector is responsible for depleting 70% of the world's freshwater supply. Unfortunately, as much as 60% of this precious resource is lost due to inappropriate irrigation systems, poor application techniques and the cultivation of water-intensive crops that require more water than is available in their growing environment (Qureshi and Ashraf 2019). This excessive water consumption is leading to the depletion of rivers, lakes and underground water sources. Several countries that produce significant amounts of food, including Australia, China, India, Spain and the United States, have already exceeded or are on the verge of exceeding their water resources' capacity (Schwab 2019). Furthermore, agriculture contributes significantly to freshwater pollution, primarily through the indiscriminate use of fertilizers and pesticides, posing a threat to humans and other species.

The above-mentioned causes are major ones across the globe, but there are a few other causes as well, which are mentioned below:

Water wastage: While some regions may not face water scarcity issues, they can still play a role in aggravating the water crisis by inefficiently using potable water (Bensen 2022).

Government policies: When a society is unable to overcome supply–demand gaps in resources such as water by responsive instructional and technological measures, institutional scarcity sets in. Similarly, political scarcity occurs when political subordination prevents a group of people from using water resources (Hussain et al. 2022). The population of certain nations, particularly those governed by dictatorial regimes may face water scarcity due to tight regulations imposed by those in power (Chakkaravarthy and Balakrishnan 2019). Such cases are profound in many developing nations, for example, Karachi in Pakistan, which is experiencing the worst water crisis in its history of the past 30 years, not as a result of a natural shortage but rather as a result of poor planning and administration (Tayyab et al. 2022). This highlights the significance of institutional concerns in managing water supplies as water scarcity can result from institutional failings that cannot sustain a steady supply (Dell'Angelo et al. 2018; Ingrao et al. 2023).

Distance: Numerous remote locations, such as deserts or secluded areas, across the globe, face water scarcity due to their lack of proximity to water sources (Rinkesh 2023) (https://www.conserve-energy-future.com/causes-effects-solutions-of-water-scarcity.php).

Insufficient infrastructure: Outdated water treatment plants, inefficient sewerage systems and leakage in poorly constructed pipes can cause the loss of billions of gallons of water (Bensen 2022).

Water scarcity: A hindrance to sustainable development

Water is a crucial resource for sustaining life on Earth, serving an essential role in both the environment and society (D'Odorico et al. 2020). As a fundamental need, water is necessary for various purposes, such as domestic use, industrial production and agriculture (Mancini et al. 2016). Sustaining water resources is also essential for current and future generations, serving critical purposes like drinking, agriculture, industry and ecosystem maintenance. The UN General Assembly recognized access to safe water as a human right and adopted SDG 6 which underscores the global commitment to ensuring water and sanitation for all by 2030. However, as a result of climate change, population growth and industrial development, water resources are becoming increasingly strained in both quality and quantity, and achieving universal clean water access remains challenging (Famiglietti 2014; Taylor et al. 2013). The statistics published by the UN in 2018 showed that more than 2.2 billion people do not have access to safely managed clean water, which affects half of schools and 25% of healthcare facilities

(Irannezhad et al. 2022). In addition, according to the World Health Organization and UN Children's Fund report, 4.2 and 3 billion people, respectively, lack access to essential sanitation and hand-washing facilities (WHO-UNICEF 2020). As a result, there is a growing consensus that the traditional approach of 'use and discard' is no longer sustainable for managing vital natural resources, including water (Chartzoulakis and Bertaki 2015).

A global scenario of water scarcity and its implications

Water scarcity has become one of the most significant problems in the 21st century, and it is projected that by 2025, 2.7 billion people will face water scarcity (UNESCO 2003). The World Economic Forum (2015) stated that water scarcity is the primary societal risk, globally, surpassing even the spread of infectious diseases, and it is anticipated to increase by 43% by 2025. By 2080, more than 56.2% of the world's population is expected to be affected by water scarcity as a high-impact and high-probability societal risk (Veldkamp et al. 2016). In 2019, a serious water crisis affected 1.8 billion people in 17 nations worldwide (Dormido 2019). Extreme weather events and changes in water cycle patterns make it challenging to access safe drinking water, particularly for vulnerable children. Over 40% of children will reside in regions with extreme water stress by 2040, and more than 1,000 children under the age of five pass away every day from illnesses linked to poor access to water, sanitation and hygiene (UNICEF 2017). Nations, such as India, Pakistan, San Marino, Botswana and Turkmenistan, are among the countries affected by water scarcity in Asia, Africa, Europe and Central Asia (Arora and Mishra 2022).

The World Resources Institute's Aqueduct Water Risk Atlas analysis also showed that 12 of the 17 countries experiencing water scarcity are located in the Middle East and North Africa (MENA) (Dormido 2019). The MENA have the greatest physical water stress due to their rapidly expanding, highly populated metropolitan centers that demand more water, as well as their lower rainfall pattern compared to other areas. Since practically, all of the food in the United Arab Emirates (UAE) is imported, less water is needed for cultivation. The desalination of plentiful ocean water, a costly and energy-intensive procedure, is also a major source of income for the UAE and other affluent MENA nations.

The local effects of physical water stress, in addition to the escalation and dissemination of freshwater pollution, are contributing to the growing prevalence of water shortage. On average, 10% of the world's population lives in countries with high or critical water stress. The number of large cities experiencing water scarcity would rise from 193 (37%) to 292 (56%) and the global urban population experiencing water scarcity would double from 933 million (33%) in 2016 to 1.693–2.373 billion (35–51%) in 2050 (He et al. 2021). A global baseline water stress interactive map was developed using the Data Basin tool (https://databasin.org/maps/new/#datasets) by the Conservation Biology Institute (CBI 2023) that indicates the major part of the United States, Europe, Middle East, Central Asia, India, China, East Asia and South-Eastern Australia fall under 'High (40–80%)' to 'Extreme (>80%)' water stress (Figure 5). Nevertheless, many of these nations, particularly the developed ones have the potential to fulfill their water demands by taking appropriate mitigation approaches and adaptation.

Due to the growing demand, developing countries, especially are located in central to northeastern Asia, western Asia and eastern and northern Africa, often lack the financial support to invest in hydraulic infrastructure (Emile et al. 2022; Lakmeeharan et al. 2020; Oki and Quiocho 2020). In addition, excessive groundwater pumping and wasteful and inefficient water management systems are further causes for worry in developing nations (Johnson et al. 2016; Winschewski 2017). The largest urban populations experiencing water scarcity reside in China (159 million) and India (222 million). By 2030, the water demand is expected to be twice the available supply, leading to severe water scarcity for millions in India. Highly

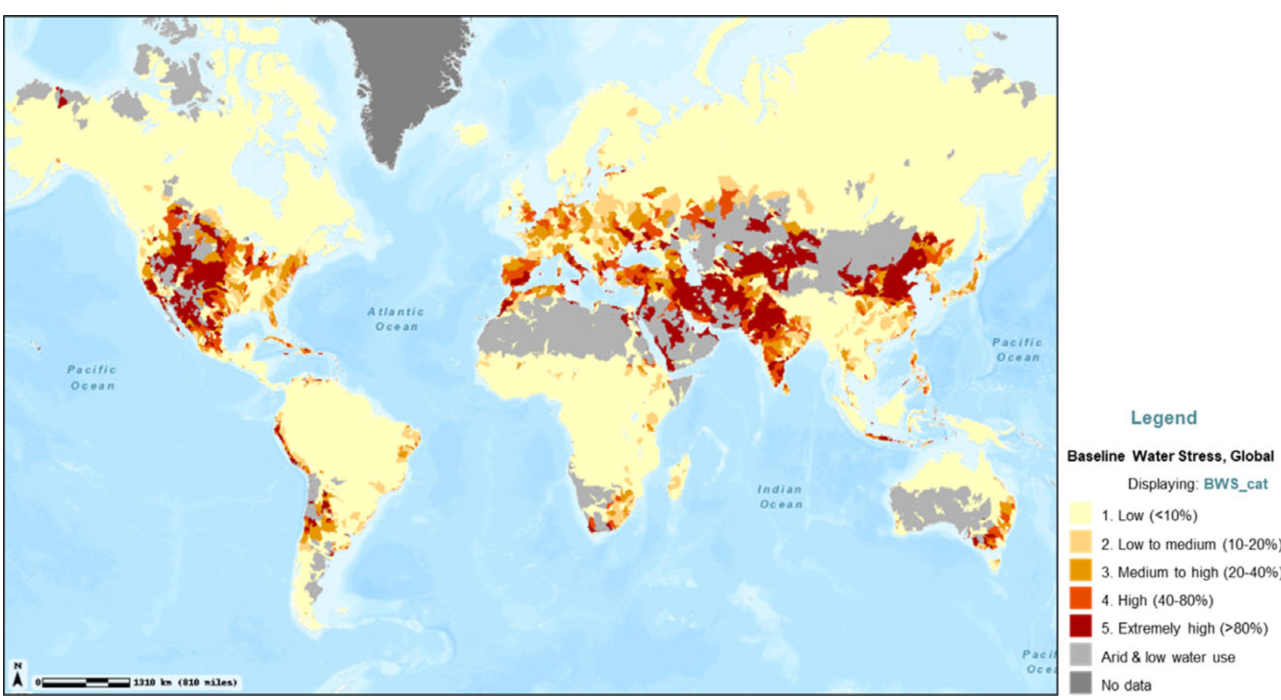

Figure 5. Global water stress severity map. The color bar in the legend (right) indicates the severity of baseline water stress from 'Low' (<10%) as 'yellow' to 'Extremely high' (>80%) as 'dark brown' in colors [data source: Data Basin, access provided by the Conservation Biology Institute (CBI), Accessed in May 2023].

populated cities like Delhi, Bangalore, Chennai and Hyderabad may reach zero groundwater levels shortly (Emile et al. 2022). Hence, appropriate measures need to be taken to reduce water usage and preserve more for a sustainable water supply in developing nations including India.

Water scarcity in India – A case example of a developing country

India is one of the world's most water-stressed countries, with only 4% of the world's water resources yet being home to 18% of the world's population (The World Bank 2023). In 2019, the NITI Aayog think-tank issued a report indicating that around 600 million individuals in India were experiencing a 'high' to 'extreme' water crisis (NITI Aayog 2019). A baseline water stress interactive map for India was developed using the India Water Tool 2.0 (IWT 2.0) software platform by the World Resources Institute (WRI 2023) that indicates ~54% of regions of India are currently facing 'high' to 'extremely high' water stress, which is profound in the western, southern and south-eastern parts of India (Figure 6). The Water Resources Group has predicted that India will experience a severe water crisis by 2030, with only 50% of its required water supply available (Mahato et al. 2022). The current usage and exploitation patterns suggest that the per-capita water availability has already decreased by approximately 75% since its independence in 1947 (Mohan 2023). The annual per capita availability of fresh water was 5,177 m^3 in 1951, which significantly came down to 1,545 m^3 in 2011 (Dubbudu 2016). The current situation suggests that this figure has further declined to 1,368 m^3 in 2019 and is anticipated to reduce even more to 1,296 m^3 by 2025. If this trend continues, the accessibility of freshwater is projected to decline to 1,140 m^3 by 2050 (Upadhyay 2020; Ritchie and Roser 2018). According to the water quality index, India is ranked 120th out of 122 countries, with almost 70% of its water supply being polluted (Srivastava et al. 2023). The report also warned that within a few years, only 21 major

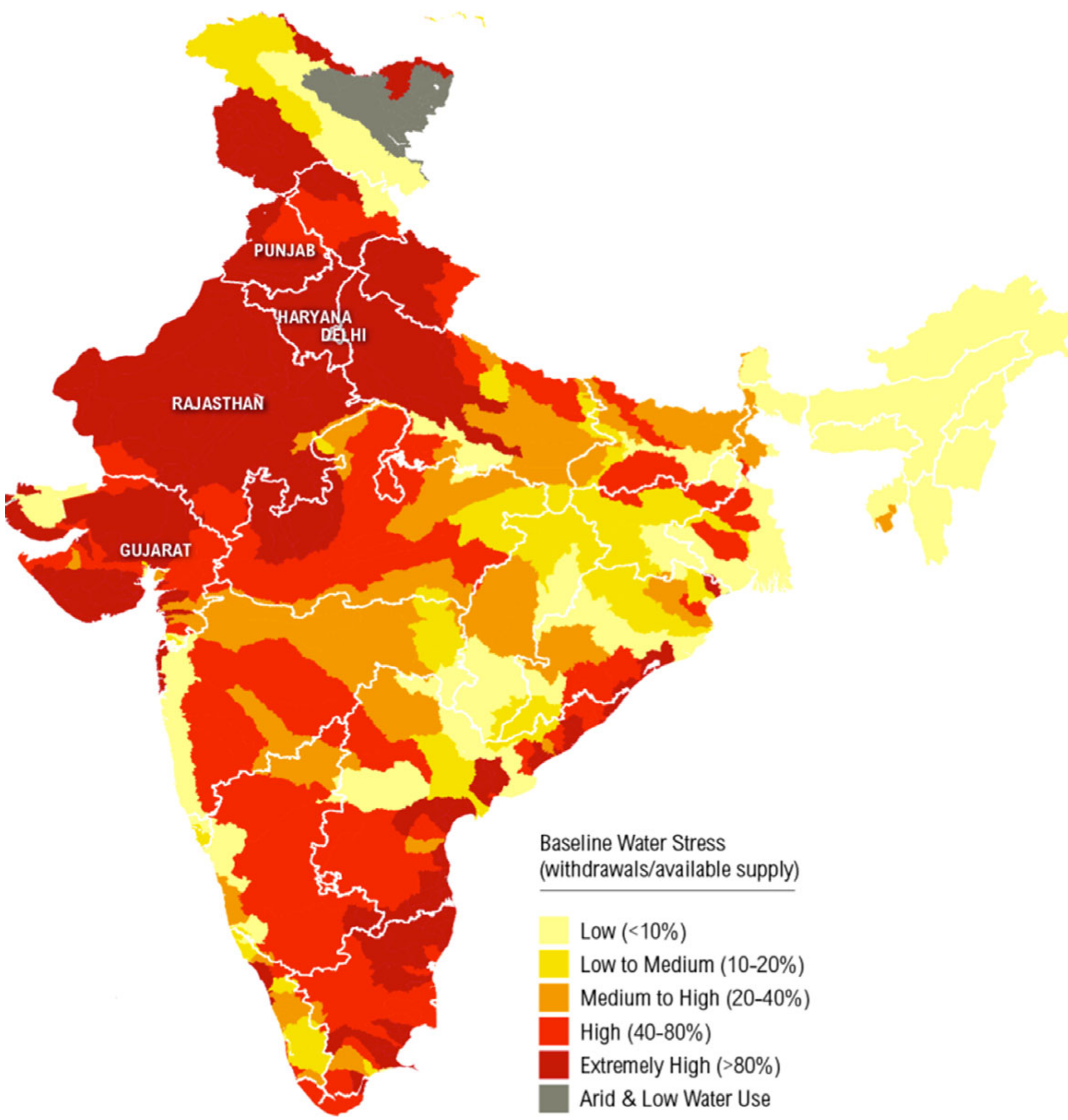

Figure 6. Baseline water stress severity map of India. The color bar in the legend (right) indicates the severity of water stress from 'Low' (<10%) as 'yellow' to 'Extremely high' (>80%) as 'dark brown' in colors [data source: India Water Tool 2.0, access provided by World Resources Institute, Accessed in 2023].

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cities, including the capital city of New Delhi, would exhaust their groundwater supplies. Back in 2019, Chennai, the southern metropolis faced an intense water shortage, prompting officials to transport water by train from approximately 200 km to salvage the situation (Ahluwalia and Kesavan 2021). However, today, Chennai has achieved a significant milestone by becoming the first Indian city to adopt large-scale recycling of its wastewater to fulfill the non-drinking water demands of its industries (The World Bank 2023). Another latest report indicated that the number of urban dwellers around the world experiencing water scarcity will reach 2.4 billion (one-third to nearly half of the global urban population), with India being the country expected to be hit the hardest (UNESCO World Water Assessment Programme 2023).

Surprisingly, more than 20 million wells are operating with free power supply, resulting in excessive water wastage, increased salinity, and rapid depletion of groundwater resources in various parts of the country (Central Water Commission 2017). The contamination of the country's water supply has reached alarming levels, with 70% of it being polluted (Schneider 2018), resulting in an estimated 200,000 deaths per year (Temple 2019). Furthermore, more than 500 million people, which accounts for 40% of the population, will lack access to drinking water by 2030 (NITI; Aayog 2019).

Water demand and scarcity in agriculture

Water requirement and crop production

Water is essential at the critical growth stages of a plant's development as at this stage, plants require an adequate amount of water to grow properly (Das et al. 2021). The critical growth stage of a plant varies depending on the type of crop, but it generally includes the period from seedling emergence to the early reproductive stage. In addition, water requirement for crops varies between crop types (Prasad 2002) (Table 1). The growth stage of a plant from seedling emergence to the early reproductive stage may require additional water supply through irrigation for proper growth and development if the natural sources of water and/or stored soil moisture in the field are inadequate. During the rapid vegetative development stage, a water shortage can reduce the height of maize plants (Cakir 2004) resulting in low yields. Likewise, Das et al. (2020) reported that water limitation can be the single largest constraint to wheat production in rain-fed conditions. For example, water stress at a critical wheat development stage has the potential to decrease yield from ~3.0 to ~1.0 t/ha within a field in Australian dryland environments (Das et al. 2020). Studies (Hatfield et al. 2011; Wang et al. 2021) report that adequate irrigation water during critical crop development stages can significantly increase the number of ears, and seeds per ear, and improve soil and air temperature, leading to increase photosynthesis and yields of maize and tomato crops. It is, therefore, crucial to manage irrigation during the critical growth stage to ensure that plants receive adequate water and maintain optimal conditions for growth and development. However, it is widely accepted that crop production improves with root zone water availability up to saturation, after which there is no influence (Hillel 1997).

Table 1. Water requirements of different crops

Crop	Water requirement (cm)
Rice (Kharif/Boro)	130–150
Wheat	45–65
Potato	35–55
Mustard	30–40
Maize	40–60 (sometimes rise up to 80)
Barley	45–65
Bajra	25–30

Adopted from (Kapuria and Banerjee 2022).

Agronomic simulation tools like the water crop productivity simulation model (AquaCrop), environmental policy integrated climate (EPIC), and agricultural policy/environmental extender (APEX) are crucial for predicting crop yields and assessing the impacts of climate change on agriculture. AquaCrop focuses on simulating crop water productivity under varying conditions, aiding in water management strategies (Steduto et al. 2009). EPIC evaluates the long-term effects of climate and management on soil and crop performance, providing insights into environmental sustainability (Williams et al. 1983). Both AquaCrop and EPIC are utilized at the farm scale, while APEX can be employed for large-scale watersheds (Feng et al. 2020). APEX also extends EPIC's capabilities by analyzing the effects of agricultural practices on large-scale watershed hydrology and crop production (Gassman et al. 2010). These tools facilitate informed decision-making by simulating future scenarios, thus supporting agricultural resilience against climate variability.

Irrigation water losses in agriculture

Approximately, 70% of the water utilized worldwide is used for agriculture, mostly for irrigation (World Economic Forum 2015). From about 40 million hectares in 1900 to more than 260 million hectares in 1999, the world's irrigated acreage has expanded more than six times (Postel et al. 2001). The 18% of cropland that is irrigated now provides 40% of the world's food. According to Jensen (1993), irrigated land grows by about 1% per year, and Rosegrant and Cai (2002) predicted that the need for irrigation water will be increased by 13.6% by 2025. When irrigation is applied to any agricultural field, not the entire amount of the irrigated water can be used by crops as some of the water can be lost during distribution and application. For example, Chartzoulakis and Bertaki (2015) reported that while applying irrigation water to a farm, a total of 35% of the water was lost during irrigation distribution, field application and farm distribution, and the remaining 65% of water was used by crops. Hence, it is necessary to ensure efficient irrigation practices to reduce losses of water during application to the field. Water use efficiency of crops can be heavily reliant on the methods of irrigation practices (Table 2). The depletion of aquifers and potential negative environmental externalities resulting from intensive groundwater pumping for irrigation have a detrimental economic impact on agriculture and related businesses.

Implications of water scarcity in agriculture – A global perspective

Water shortage is a threat to agriculture, globally (UNESCO World Water Assessment Programme 2018). Its consequences can be disastrous, resulting in failed crops, lower yields, food insecurity and the abandonment of lands. Over the past 40 years, water demand in agriculture has grown globally by about 1% per year

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Table 2. Country-wise different irrigation methods for optimum water use efficiency

References	Nation	Vegetation/crops	Method of irrigation	Approach	Conservation of water (percentage)	Additional information
Liao et al. (2021)	China	Tomato	Drip	Soil moisture	3	More water use efficiency through irrigation when compared with the control group
Krishnan et al. (2020)	India	Not available	Drip	Soil moisture along with rain sensor	13–41.5	The motor has been used for 9.72% of the total time requirement to water
Barkunan et al. (2020)	India	Tomato	Drip	Either soil sensor or rain sensor	Not available	Not available
Cruz et al. (2020)	Malaysia	Mustard	Drip	ET controllers	72	No effect has been observed on yield
Bodunde et al. (2019)	Nigeria	Not available	Sprinkler irrigation by robot	Soil moisture	Not available	Reduced harm on crops and land due to system installation
Panigrahi et al. (2019)	India	Banana	Drip	Soil moisture	20	15% increase in yield
Reghukumar and Vijayakumar (2019)	Not available	Basil	Drip	Soil moisture	Not available	Possible to forecast plants' health by using a decision tree model
Barkunan et al. (2019)	India	Rice	Drip	Rain sensors	41	Not available
Isik et al. (2017)	Turkey	Walnut	Drip	Soil moisture	23	Labour requirement has reduced by 60%
Zhang et al. (2017)	China	Citrus	Drip	Soil moisture sensor	20	More yield with increased solid part in fruit
Isik et al. (2017)	USA	65% St. Augustine grass with 35% of mixed ornamentals	Sprinkler	ET controllers	3–26	The negative impact of site-specific precipitation on scheduling efficiency
Al Ghobari et al. (2016)	Saudi Arabia	Tomato	Drip	ET controller	18	Lowest requirement of water and maximum yield when compared with the control system
Dobbs et al. (2014)	USA	Bahia grass	Sprinkler	ET controllers	66–70	Decrease in percolation of NO_3—N and NH_4-N
				Soil moisture sensors	64–75	
				Rain sensors	17–49	
Grabow et al. (2013)	USA	Turfgrass	Sprinkler	ET controllers	11	Better turf quality
Rutland and Dukes (2012)	USA	St. Augustine grass with mixed ornamentals	Sprinkler	ET controllers with rain sensor	41	Not available
Ooi et al. (2010)	Australia	Apple	Manually done irrigation	Soil moisture sensors	33	No changes in yield
Migliaccio et al. (2010)	USA	Papaya	Drip	Soil moisture sensors	68	Growth, yield, photosynthetic rate, and nutrient amount have been continued.
				ET controllers	65	
McCready et al. (2009)	USA	St. Augustine grass	Sprinkler	Rain sensor	7–30	Proper turf quality is achieved with 1 day/week 6 mm treatment
				Soil moisture sensor	11–53	Good quality yield by using a medium threshold setting
				ET controller	25–62	Good turf quality by using toro treatment

due to a combination of this massive population expansion, socio-economic development and changing consumption habits (Department of Economics and Social Affairs, Population Division 2017). A report revealed that municipal withdrawals rose by 3% between 2010 and 2018, while agricultural withdrawals rose by 5% (Food and Agriculture Organization 2020). The demand for water

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in global agriculture will increase by 60% by 2025 (Alexandratos and Bruinsma 2012).

In California, United States, the ongoing drought has had a significant impact on agriculture. California is a leading agricultural state in the United States and the crop production relies heavily on irrigation. However, the drought has reduced the availability of water for irrigation, leading to significant losses in agricultural production. According to a report by the University of California, the drought in 2015 resulted in a $1.84 billion loss in agricultural revenue and the loss of 10,100 seasonal jobs (Kerlin 2015). In addition, the farmers in California have had to reduce their planting area or leave farmland fallow due to the limited availability of water for irrigation. It also emphasized how water shortage is a problem in many of the world's key agricultural regions and that it will probably persist in the years to come. Water shortages and climate change might cause a 23% drop in global food output by the year 2,100 (Schewe et al. 2014). The study also highlighted that water scarcity will be the primary driver of food production loss in many regions across the world, including the Middle East, North Africa, South Asia and Southern Europe. The UN (UNESCO 2022) predicted that by 2030, water scarcity could reduce crop yields by 20% globally causing a 'significant threat' to food security. By 2040, water shortage may threaten up to 30% of the world's food production (Zhang et al. 2021). In the Mediterranean area, water shortage might threaten up to 40% of the region's overall crop revenue by 2040 (Mekonnen et al. 2020). Wheat and maize production might decrease by 10–20% because of water constraints by 2050 in Southeast Asia (Gupta et al. 2021). In Pakistan's Indus River Basin, it was reported that lack of water has significantly reduced agricultural productivity and compelled farmers to switch from water-exhaustive crops like rice to less water-intensive crops like wheat (Shah et al. 2019). Due to the lack of access to irrigation technology and low financial resources, smallholder farmers in developing and underdeveloped countries are especially exposed to the consequences of water shortage (Djaman et al. 2018). In sub-Saharan Africa, 95% of smallholder farmers rely on seasonal rainwater for crop production (Giller et al. 2011).

India, with over 600 million farmers of a total of 1.4 billion population, stands as the second-largest wheat and rice producer globally, contributing to 10% of the world's crop production (Erickson 2021). However, extensive usage of groundwater has made India one of the largest consumers of water resources in the world, facing high water stress and having particularly fragile water resources (Carrington 2016). The excessive pumping of groundwater through tube wells has enabled Indian farmers to increase their food production significantly since the 1960s, even during dry seasons which has resulted in 'critically low groundwater availability' in the northwest and south regions of the country (Jain 2018). The severe impact of water scarcity was noticeable in early 2016 when 300 million Indians encountered acute water scarcity due to two consecutive seasons of weak monsoons, resulting in a significant decline in farm production (Bera 2017). Due to the same reasons, India experienced a decline in sugar production from a peak of 28.3 million tons in 2013–2014 to 25.1 million tons in 2015–2016, and a seven-year low of 21.3 million tons during 2016–2017 (Bera 2017). Due to increasing water scarcity, many farmers are switching crops, for example, in the state of Tamil Nadu, farmers have switched to cultivating sesame instead of groundnut due to its low water requirement (Haq 2023). Some studies also indicated that if farmers in areas where groundwater is being excessively extracted were to lose access to it entirely without having any other alternative sources of irrigation water to compensate. This could lead to a 20% decline in winter harvests nationwide, with the most severely impacted regions experiencing a 68% reduction (Yeung et al. 2021). By the year 2030, 74% of the total wheat-cultivated land and 65% of the rice-cultivated land in India will encounter notable water scarcity (NITI; Aayog 2019). A 36-years age farmer possessing 17 acres (7 ha) of agricultural land in the state of Punjab in India, had told in an interview that farmers in his region were able to produce only 8 quintals (800 kg), compared to the typical yield potential of 18 quintals (1,800 kg) per acre of wheat cultivation. As a cause of this drastic fall in wheat production, he accused water scarcity arising out of rising temperatures and erratic rainfall (Guram 2022). To tackle this critical situation, many young farmers are adopting millet farming in Punjab as a profitable substitute for rice and/or wheat due to its low water requirement (Bhogal et al. 2022).

Prospects to adopt viable approaches to managing agricultural water

The time has come to consider the adaptation of existing water harvesting technologies to circumvent the situation of grave water scarcity arising out of the indiscriminate use of underground water to enhance crop productivity. The strategic factor for the selection of a particular water-conserving technique, the most essential criterion is to consider the 'efficiency' parameter, both in terms of utilization and conservation of each of the available techniques (Figure 7).

Evaluating prices and markets of water in agricultural water use for sustainable development

Prices and markets for water, along with institutional frameworks, play a critical role in ensuring the sustainable development of agricultural water use by promoting efficiency, equitable access and conservation. Hence, it is important to evaluate prices and markets of water. Water pricing mechanisms, such as volumetric pricing or tiered tariffs, can encourage farmers to use water more efficiently, reducing waste and over-extraction from aquifers. Several studies highlight the crucial role of water pricing and market mechanisms in promoting sustainable agricultural water use. Water pricing policies, when designed effectively, can incentivize farmers to adopt more water-efficient practices, thus improving water productivity. For example, In Iran, the implementation of such policies led to a notable shift toward optimizing water use due to the economic pressures associated with higher water costs. Markets for water can also enable more efficient allocation, allowing scarce water resources to be used where they generate the highest agricultural returns (Zamani et al. 2020). Furthermore, In Brazil's semi-arid areas, the implementation of water pricing policies can significantly reduce agricultural water use by incentivizing farmers to adopt more efficient irrigation methods, shift to less water-intensive crops and invest in water-saving technologies. This approach helps alleviate the effects of water scarcity, particularly during droughts (Marengo et al. 2022). However, it is essential to carefully design pricing structures to maintain fair access for small-scale farmers and prevent adverse economic effects on vulnerable communities. Similarly, water markets, which allow for the trading of water rights, help in allocating water resources where they are most valued, increasing overall economic efficiency. Australia's Murray-Darling Basin provides a notable example where water trading facilitated more efficient use, resulting in higher agricultural productivity and improved environmental outcomes (Grafton et al.

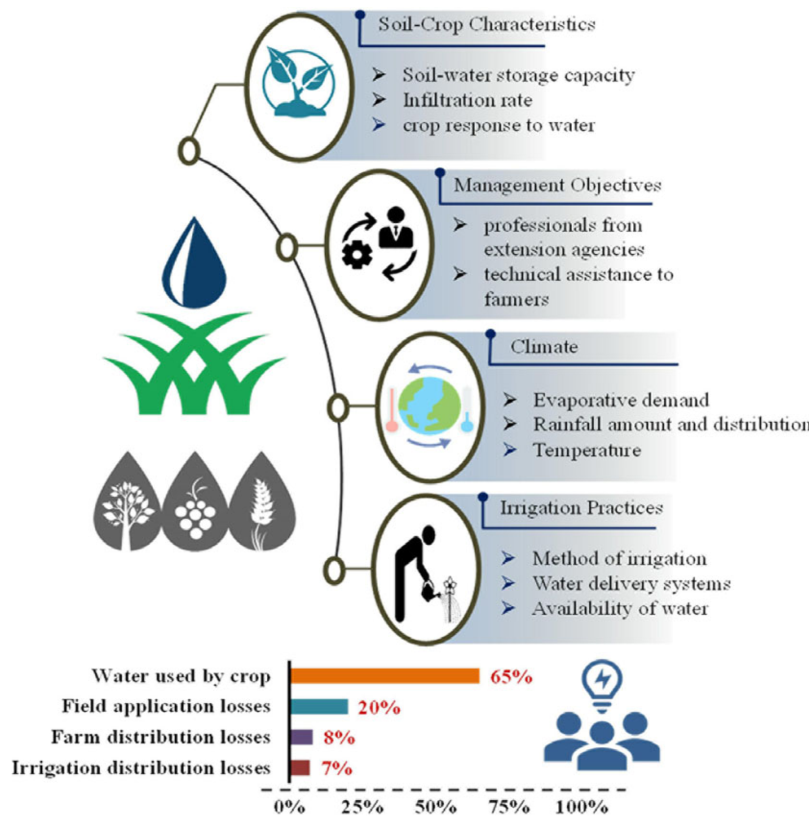

Figure 7. Components of irrigation scheduling for increasing water usage efficiency using marginal waters for irrigation in agriculture.

2012). Institutional frameworks, including legal and regulatory systems, also play a crucial role. Effective water governance, such as establishing clear water rights and regulatory oversight, ensures that water allocation aligns with long-term sustainability goals. For example, the European Union's Water Framework Directive mandates sustainable water use across sectors, promoting the protection of water ecosystems while supporting agricultural needs (European Commission 2019). These mechanisms – pricing, markets and governance – work in synergy to balance water demand and supply, fostering sustainable agricultural practices.

Improved irrigation systems

Water resources management is the planning, development and administration of water resources concerning water quantity and quality across all water uses (Figure 8). It is made up of institutions, schemes for financial assistance, information systems and groups

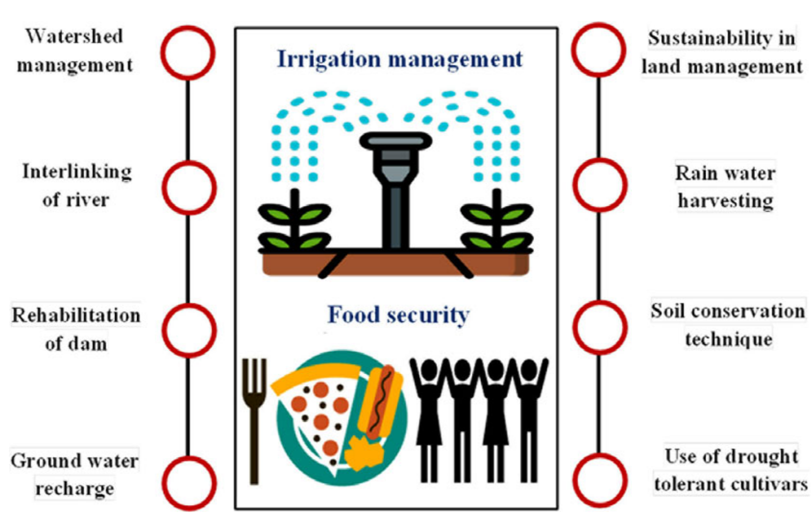

Figure 8. Improved management of water resources concerning water quantity and quality across all water users.

that support and guide water management. Some of the components of an improved water management practice are discussed below and depicted in Figure 8.

In arid and semi-arid areas, the rising demands for water from municipal and industrial sectors continuously diminish the water allotment for agriculture (Mirdashtvan et al. 2021). Consequently, water availability is generally restricted, which inevitably leads to sub-optimal crop yields. To optimize the use of water resources, improved irrigation techniques that do not rely on meeting the full CWRs need to be implemented. These include deficit irrigation, partial root drying and sub-surface irrigation. It is also essential for improving the performance and sustainability of irrigation systems. In order to decide when to irrigate and how to irrigate, an understanding of crop water needs, weather and soil characteristics is necessary. The proficiency of the farmer significantly impacts the efficacy of irrigation scheduling at the field level. A suitable irrigation schedule has the potential to hinder deep percolation and the movement of fertilizers and agro-chemicals outside the root zone, avoid waterlogging, save water and energy and result in higher yields and better-quality crops (Chartzoulakis and Bertaki 2015). In addition, some common and widely adopted irrigation practices such as micro-irrigation and fertigation are useful for managing agricultural water use.

Micro-irrigation

Micro-irrigation is a method of applying water to plants at a slow and targeted rate, typically using low pressure. Sub-surface drip, trickle irrigation, micro-sprinklers and bubblers are some of the most common methods used in a micro-irrigation system. The system consists of small-diameter tubing that is placed either on the surface or underground in the field, with small water application devices attached to the tube to supply water directly to the plants at low pressure (Evans et al. 2007). This technique is essential for conserving water while achieving optimal plant growth. Micro-irrigation systems are particularly useful for widely spaced trees, vine crops and high-value vegetable crops. However, one of the main drawbacks of micro-irrigation is its high installation cost, as well as the increased risk of clogging, particularly when low-quality water is used (Barragan et al. 2010).

Fertigation

Fertigation is a popular technique in modern agriculture where fertilizers are applied through the irrigation system. It is well-suited for localized irrigation systems that are highly efficient for water application (Shukla et al. 2018). Fertigation involves the direct application of soluble fertilizers to the wetted volume of the soil at recommended concentrations for crops through the irrigation system. However, there are some potential drawbacks to fertigation. These include non-uniform distribution of chemicals when irrigation design or operation is inefficient, fertilization above actual crop needs and excessive utilization of soluble fertilizers.

Modern water-saving agricultural practices

Conservation tillage

Conservation tillage (CT) is a farming practice that involves leaving crop residues on the field after harvest to retain moisture and prevent soil erosion. This method can reduce water use by up to 50% compared to conventional tillage (Kaur and Jat 2017). The CT can also improve soil health and reduce soil degradation caused by excessive water use. Additionally, it improves soil structure, reduces soil compaction and increases soil organic matter, which can contribute to more efficient water use and improved crop yields (Jat et al. 2013). This type of tillage also helps to increase soil moisture retention and improve crop yield in dryland farming systems (Govaerts et al. 2009). It is a promising agricultural practice for efficient water use in India, where water resources are limited, and soil degradation is a major concern. It reduced water use by up to 40% compared to conventional tillage practices in Haryana (Singh et al. 2017) whereas in the western state of India, mainly in Gujrat, water use was reduced by 30% with an increased yield of 20% due to this special type of practice (Gajri et al. 2013). Conservation tillage (Reduced tillage and Zero tillage) also improves bio-meteorological parameters including leaf area index, photosynthetically active radiation use efficiency (PARUE) along with biological and grain yield compared to conventional tillage in the case of maize during rabi season (Pal et al. 2022). It is also a less labor-intensive as well as less capital-intensive technique but plays a vital role in enhancing productivity. A study that took place in the cotton-growing community of Refugio County, Texas, showed that every 1% adaption of CT could turn a county-wide benefit of approximately USD $16,000 (Cusser et al. 2023).

Crop shifting

Crop shifting involves planting crops that require less water during dry seasons or in water-limited areas. This can help to reduce the amount of irrigation water needed and prevent soil degradation caused by excessive water use (Acharjee et al. 2019). For example, in the lower Indo-Gangetic plain, traditionally, Boro rice and potato are cultivated, but these crops are highly irrigation intensive causing a steady reduction of groundwater level. Farmers are being recommended to pick maize over rice in order to avert this catastrophe because it uses just one-fifth as much water to cultivate as rice, yields more and offers greater returns to farmers (Kapuria and Banerjee 2022).

Crop rotation

Crop rotation is a practice where different crops are grown in sequence in a year on the same piece of land. Certain crops like legumes can fix nitrogen in the soil, reduce the need for fertilizers, and therefore reduce water use. As an example, rice-based cropping is the conventional system in lower Indo-Gangetic plains in India, but in recent times, legumes like cowpea, Lathyrus, Bengalgram, Greengram and Blackgram have been incorporated (Lauren et al. 2008). For example, lentils and chickpeas were successfully cultivated during the rabi season of 2018–2019 and 2019–2020 with residual soil moisture after monsoon rice at the B.C.K.V., Kalyani, West Bengal (Mukherjee 2022). Irrigation facility was not applied for these two winter legumes cultivation which not only saved water application as compared to boro rice cost but also generated additional income. Thus, such kind of crop rotations can be beneficial in the current water-scarce scenario.

Mulching

Mulching is an approach that involves covering the soil around the plants with organic materials, such as leaves or straw. In dryland conditions, mulching is an effective method for conserving water, as it helps to maintain soil moisture, lower soil evaporation and control temperature (Kader et al. 2017). It is also extensively used in rain-fed farming systems to save water (Chakraborty et al. 2008; Zribi et al. 2015). Plastic sheet mulching is more effective in conserving soil water than wheat straw mulch (Li et al. 2013). The primary benefit of mulching is its ability to retain soil moisture by preventing soil erosion and reducing surface evaporation (Qin et al. 2016). This, in turn, reduces the need for irrigation during crop cultivation seasons, making mulching a cost-effective and sustainable method for conserving water (Kader et al. 2017).

Use of drought-tolerant crops

Planting drought-tolerant crops can reduce water use and increase crop yields under water-limited conditions (Das et al. 2022). These crops have been developed through breeding programs to survive and produce in dry conditions, making them an ideal choice for areas with low water availability. Different varieties (like Huhan-3, Huhan-7, water-saving and draught-resistant rice (WDR) 48, etc.) of WDR are popular and acceptable among farmers in different parts of China (Luo et al. 2019).

Other demand-side practices

While the review primarily focuses on water scarcity and its relation to agricultural water management practices as the agricultural sector is the major contributor to the global water crisis, other demand side practices, such as permits, pricing electricity, well spacing requirements and water markets could also be considerable factors, as well. For instance, water pricing mechanisms, such as volumetric pricing or tiered pricing strategies, have been shown to effectively promote water conservation in agriculture by incentivizing farmers to adopt water-saving technologies and practices only when water prices reflect their scarcity (Loch and Adamson 2015). Moreover, institutional measures like well-spacing regulations can directly impact groundwater sustainability, preventing over-extraction and ensuring equitable water distribution among users (Molle and Closas 2020). Likewise, the establishment of water markets, which allow the trading of water rights, has been successfully implemented in regions like Australia's Murray-Darling Basin, where such markets enable more efficient water allocation between agricultural and non-agricultural users during periods of scarcity (Grafton and Horne 2014). These examples highlight the importance of combining agricultural interventions with policy and market-driven measures to optimize water use. Furthermore, it is also necessary to consider how the timing, geographic context and socio-economic conditions determine the adoption of both agricultural and institutional practices. For instance, while precision irrigation technologies, such as micro-irrigation and fertigation, may be critical in areas with high-value crops, institutional solutions like water permits and electricity pricing could be more effective in regions with over-reliance on groundwater or where energy subsidies distort water use behavior (Ma et al. 2022). Integrating these considerations would provide a more comprehensive roadmap for achieving sustainable agriculture and water use.

Furthermore, Table 4 summarizes a critical analysis of country-wise water-use efficient techniques, their prevalent conditions, costs and benefits, advantages and limitations.

Agricultural water management – Technological innovations and adoption

Use of super-absorbent polymer hydrogels

Hydrogel is a type of gel in which the liquid constituent is water. Being a hydrophilic substance, they can absorb and retain aqueous solutions that can be up to a hundred times their weight (Buchholz and Graham 1998). They have various positive effects on soil, including a better infiltration rate (Helalita and Letey 1989). They also act as soil conditioners by reducing evaporation rate and moisture stress (Gehring and Lewis 1980; Teyel and El-Hady 1981). In floricultural crops, they enhance the ability to retain water in pot soil (Eikhof et al. 1994). They also regulate the discharge of pesticides (Rudzinski et al. 2002), along with water conservation (Nnadi and Brave 2011), and protection against soil erosion (Sojka and Lentz 1997), which makes it an ideal component for various water-saving applications in agriculture.

Precision agriculture

Precision agriculture is the science and technology that uses data-driven approaches from ultra-high resolution ground-based and aerial sensors and analytical tools, which improve crop productivity and increase the cost-effectiveness of resource management including irrigation management, fertilizer management and pesticide application (Friedl 2018). It is an innovative approach where farmers can improve productivity, quality and quantity of yield by supplying optimized inputs such as water and fertilizer. Advancements in technology, particularly the accessibility of high-quality satellite images and the swift progress of unmanned aerial vehicle technology, indicate that the utilization of remote sensing technology and the use of big data in precision agriculture is expected to see a rapid upsurge in the next few years (Friedl 2018).

Table 3. Description of different types of rainwater harvesting systems

Types	Description	Advantages	Disadvantages
Deep tillage	Uptaking soil water and nutrients at deep horizons by promoting root proliferation, reducing surface sealing of the soil and increasing porosity.	• Economically viable • Simple establishment	• Occurrence of soil erosion • Not applicable in dry situations
On-farm reservoir	Storing rainwater in a reservoir, trenched at nearby farms for irrigation purposes during summer.	• Sustainability • Capacity can be fixed based on crops' need	• Chances of being expensive due to soil health • Reduction of farming area
Roof catchment system	Collecting rainwater through rooftops and directed toward a reservoir	• Requires 111 house roofs for a good catchment area	• Claims proper pipe system for collecting rainwater from different house roofs • High cost of maintaining
Artificial groundwater recharge	Directing Rainwater toward underground aquifers that can be drained out and used later	• No need for separate tanks for storing water • No requirement for complicated construction	• Possibility of not getting water due to gravitational force during the summer season

Adopted from (Varma et al. 2021).

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Table 4. A summary of the country-wise adapted water-use efficient techniques

Continent	Country	Crop taken	Prevalent condition	Water-use efficient technique	Initial cost of investment	Specific benefits	Advantages	Disadvantages	References
Europe	South Portugal and Spain	High-valued crops like grape vine, olive, etc.	Generally, rainfed; irrigation is redistricted in Portugal but in Spain, farmers use conventional irrigation processes	Partial root drying (PRD) under deficit irrigation technique.	\$410–700 ha^{-1} (depends on the region)	Water savings up to 60%, yield increase up to 40%	High water-use efficiency, reduces evaporation, minimizes weed growth	High initial setup cost, requires regular maintenance and skilled labor	Romero et al. (2022); Azorin and Garcia (2020)
South America	Brazil	Food crops mainly rice	Tropical and subtropical regions with high soil erosion risks and reliance on rain-fed agriculture	Conservation tillage	\$60–\$120/ha (depending on machinery used)	15–30% increase in water infiltration, 10% yield improvement	Reduces soil erosion, improves water retention, less labor-intensive	Can lead to compaction or hard pan issues, and may increase herbicide use	Fuentes-Llanillo et al. (2021); Anghinoni et al. (2021)
	Brazil	Vegetables (tomato)	Fall–winter growing season when rainfall and humidity are lower	Plastic film mulches	\$820/ha	33–34% increase in yield	Improves soil moisture retention, reduces weed growth, inexpensive	Decomposition issues require regular replacement depending on the material used (organic/inorganic)	Mendonça S et al. (2021)
	Mexico	Maize	\$1,500–\$3,000/ha	Subsurface drip irrigation	\$1,530–\$3,200/ha	Water savings up to 50%, 10–15% yield improvement	Minimizes evaporation and runoff, reduces water usage significantly, improves root zone moisture	High installation and maintenance costs, difficulty in detecting leaks or blockages	Mansour et al. (2020)
Asia	Israel	Suitable for high-value crops (e.g., fruits, vegetables).	Arid and semi-arid regions with limited freshwater availability	Drip irrigation	\$500–\$2,000/ha	Water savings up to 60%, yield increase up to 40%	High water-use efficiency, reduces evaporation, minimizes weed growth	High initial setup cost, requires regular maintenance and skilled labor	Tal 2021); Yasuor et al. (2020)
	India	Rice and wheat cultivation	Rainfed and uneven terrain affects water distribution	Laser land leveling	\$200–\$350/ha	20–30% water savings, 10–15% yield increase	Improves water distribution, reduces runoff, efficient for rice and wheat	Expensive initial investment, specialized machinery required	Aryal et al. (2020); Saxena et al. (2020)
	Philippines	Paddy field	Seasonal monsoon and frequent droughts	Alternate wetting and drying	\$50–\$100/ha	15–30% reduction in water use, 5–10% yield improvement	Reduces methane emissions, and BPH infestation, improves water use in rice paddies, cost-effective	Requires precise water management, not suitable for all soil types	Yokoyama et al. (2011); Enriquez et al. (2021)
	China	Vegetables like tomato	Semi-arid and temperate regions where evaporation is the prime problem	Residual mulching	\$200–\$400/ha	20% water retention increase, reduces evaporation by 25%	Same as plastic mulching	Same as plastic mulching	Zhang et al. (2016)

(*Continued*)

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Table 4. (*Continued*)

Continent	Country	Crop taken	Prevalent condition	Water-use efficient technique	Initial cost of investment	Specific benefits	Advantages	Disadvantages	References
	Brazil	Cereals crops to JUJUBE cultivation	In flooded rainy season and rainfed conditions, dark gray, acidic heavy clays	Shifting of cropping pattern	$1,580–$2,300/ha	Jujube farmers got a 68% higher gross return compared to conventional wheat black gram cultivation; the Gross margin was 72% higher than the wheat-jute-vegetables pattern.	Helps to make socio-economic change by cultivating high-valued crops	The initial cost of cultivation is higher than	Khandoker et al. (2014)
North America	USA	Corn and wheat	Regions with moderate water stress, suitable for large-scale fields with uniform terrain	Sprinkler irrigation	$1,000–$2,500/ha (system cost)	30% water savings compared to surface irrigation	Suitable for a variety of crops, reduces soil erosion, easy to automate	Wind drift can cause uneven water distribution, high energy consumption	Kresović et al. (2016)
Oceania	Australia	Vegetables	Temperate climate with extended summers; and cold winters. Rainfall on average is 619 mm per year and high evaporation rates.	Soil moisture sensors	$1,000–$3,000/ha	20–30% water savings	Optimizes irrigation scheduling, reduces water wastage, improves yield consistency	The high cost of equipment and installation requires technical knowledge	Malone et al. (2024)
Africa	Kenya	All types of crops mainly food crops	Arid and semi-arid regions where rainwater is scarce but can be stored for use during dry periods. Especially for small-holding farmers	Rainwater Harvesting	$500–$1,500 (per farm setup)	Increase water availability by 20–50% during dry seasons	Increases resilience to drought	Expensive setup for large scale, maintenance required to keep storage systems functional	Odhiambo et al. (2021)
	Ghana	Maize	The northern part where draught is a frequent phenomenon	Draught tolerant variety	No cost was involved as it was a part of the project run by the International Maize and Wheat Improvement Center (CIMMYT) and International Institute of Tropical Agriculture (IITA).	Increase in yield by 150%.	Significant impact in increasing crop yield as well as income of the farmers and has good market demand.	Availability and accessibility to the farmers are tough and purchasing is comparatively high as production costs are high.	Martey et al. (2020)

Rainwater harvesting

Rainwater from roofs, rooftop terraces and impermeable surfaces is collected, stored, treated and distributed for on-site consumption through a rainwater harvesting system (Campisano et al. 2017). In developing countries, this system remains the ultimate source of water supply for millions of people (Kim et al. 2016). However, usage of rainwater harvesting is highly encouraged even in developed countries by laws, as a sustainable way to increase the resilience of the water supply. There are multiple types of rainwater harvesting methods available with various merits and demerits (Table 3).

Solar-powered water pumping systems

The purpose of a solar water pumping system is to minimize the use of coal-based electricity and diesel fuel photovoltaic (PV) pumping is one of the most adopted solar energy-operated water pumping systems, in rural villages in many developing countries. The size of the PV array and the amount of solar radiation determines the flow rate of pumped water. When compared to a traditional pumping system, a well-designed PV system yields considerable long-term cost savings with a minimum water application rate (Kumar et al. 2020).

Cloud-based irrigation system

A cloud-based irrigation system consists of soil moisture and humidity sensors, Arduino Uno, central cloud storage and mobile apps. Soil moisture and humidity sensors are used to continuously gather data on soil moisture and humidity. The Arduino Uno gadget receives this information which is delivered to a centralized cloud. Mobile applications are connected to this cloud. Farmers can use mobile applications to set the values for moisture and humidity. Furthermore, a smart irrigation system will activate sprinklers or water pumps if the farmer's specified range for soil moisture and humidity is met (Kaur et al. 2024).

Conclusions

Water scarcity can be caused either due to man-made incidences or natural events, but it has disastrous effects on the well-being and prosperity of billions of people, globally. In the coming years, numerous regions around the world, including India, will need greater freshwater resources to fulfill the enormous demands of water and food in the face of the uncertainties of climate fluctuations and other environmental constraints. Various studies have highlighted the common practices of over-exploiting natural resources in India, especially affecting soil health and groundwater table. As 80% of total water consumption goes to the Agricultural sector in India, it has a significant role in averting the aggravation of this critical situation. With almost half of the Indian population being engaged in this sector, a decline in the growth rate by a huge drop in the gross domestic product will be a negative consequence due to water-related losses. In order to address this globally critical issue, the UN has included it as one of the primary objectives of Sustainable Development Goal-6 (SDG 6), which states 'to ensure availability and sustainable management of water and sanitation for all by 2030'. A total of eight targets come under SDG 6 which takes into consideration – safe and affordable drinking water by 2030 (target 6.1), services for sanitation and hygiene (target 6.2), treatment and reuse of wastewater, improvement of water quality (target 6.3), increasing water use efficiency and freshwater supplies (target 6.4), implementation of integrated water resources management (target 6.5), protection and restoration of water-related ecosystems (target 6.6), international support and capacity building support (target 6A) and lastly, support and strengthen the participation of communities in water and sanitation management (target 6B) (https://sdgs.un.org/goals). To achieve this target, specific adaptation strategies for water management should be followed that have been discussed thoroughly in this study including evaluating water pricing and markets, adaptability of various water-use efficient techniques and their costs and benefits across different regions, improved irrigation systems, such as micro-irrigation, fertigation, deficit irrigation and so on, modern water-saving agricultural practices like conservation tillage, crop shifting, crop rotation, mulching, use of drought tolerant crops. Additionally, innovative technologies for water management approaches like the use of super-absorbent polymer hydrogels, biochar and precision agricultural practices are also discussed to provide a thorough understanding.

Overall, this review enhances our existing knowledge by synthesizing the current research, case studies and policy frameworks. The paper consolidates insights on the complex interactions between water scarcity and agricultural demands, highlighting how water shortages exacerbate food insecurity, increase vulnerability of livelihoods and obstruct progress toward the UN SDGs. By critically evaluating the effectiveness of adaptation strategies including technological innovations, water management policies and sustainable agricultural practices, this review equips researchers with a comprehensive understanding of the science and gaps in current research. Furthermore, practitioners and policymakers will find valuable information and recommendations to guide water-efficient agricultural practices, inform equitable water distribution policies and develop actionable plans to counter the global water crisis. This synthesis of impacts and solutions is crucial for fostering resilience in water-scarce regions and promoting global sustainability in the face of growing environmental pressures.

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References

Acharjee TK, **Van Halsema G**, **Ludwig F**, **Hellegers P and Supit I** (2019) Shifting planting date of Boro rice as a climate change adaptation strategy to reduce water use. *Agricultural Systems* **168**, 131–143. https://doi.org/10.1016/j.agsy.2018.11.006.

Ahluwalia P and Kesavan R (2021) Chennai Becomes First Indian City to Recycle Wastewater at Scale. *World Bank Blogs*. Available at https://blogs.worldbank.org/endpovertyinsouthasia/chennai-becomes-first-indian-city-recycle-wastewater-scale.https://blogs.worldbank.org/endpovertyinsouthasia/chennai-becomes-first-indian-city-recycle-wastewater-scale (accessed 18 April 2023).

Ahopelto L, **Veijalainen N**, **Guillaume J**, **Keskinen M**, **Marttunen M and Varis O** (2019) Can there be water scarcity with abundance of water? Analyzing water stress during a severe drought in Finland. *Sustainability* **11**, 1548. https://doi.org/10.3390/su11061548.

Akpor OB and Muchie M (2011) Environmental and public health implications of wastewater quality *African Journal of Biotechnology* **10** (13), 2379–2387. https://doi.org/10.5897/AJB10.1797.

Al Ghobari HM, **Mohammad FS and El Marazky MS** (2016) Evaluating two irrigation controllers under subsurface drip irrigated tomato crop *Spanish Journal of Agricultural Research* **14** (4), 29–40.

Alcamo J, **Henrichs T and Rosch T** (2000) World water in 2025. *World Water Series Report*, *2*. Available at http://www.env-edu.gr/Documents/World%20Water%20in%202025.pdf.

Alexandratos N and Bruinsma J (2012) World Agriculture Towards 2030/2050: The 2012 Revision. ESA Working Paper No. 12–03. Agricultural Development Economics Division, FAO.

Allan JA (1993) Priorities for water resources allocation and management. *Fortunately, there are substitutes for water otherwise our hydro-political futures would be impossible. ODA, London.*

Alotaibi BA, **Baig MB**, **Najim MM**, **Shah AA and Alamri Y A** (2023). Water scarcity management to ensure food scarcity through sustainable water resources management in Saudi Arabia. *Sustainability*, **15**(13), 10648. https://doi.org/10.3390/su151310648.

Amarasinghe UA (2007) India's Water Future to 2025–2050: Business-as-Usual Scenario and Deviations. *Colombo, Sri Lanka: International Water Management Institute, Research Report No. 123.*

Anghinoni G, **Anghinoni FBG**, **Tormena CA**, **Braccini AL**, **Mendes IDC**, **Zancanaro L and Lal R** (2021) Conservation agriculture strengthen sustainability of Brazilian grain production and food security. *Land Use Policy*, **108**, 105591. https://doi.org/10.1016/j.landusepol.2021.105591.

Arora NK and Mishra I (2022) Sustainable development goal 6: Global water security *Environmental Sustainablity*, **5**, 271–275. https://doi.org/10.1007/s42398-022-00246-5.

Aryal JP, **Khatri-Chhetri A**, **Sapkota TB**, **Rahut DB and Erenstein O** (2020) Adoption and economic impacts of laser land leveling in the irrigated rice-wheat system in Haryana, India using endogenous switching regression. *I*Natural Resources Forum, **44** (3), 255–273. https://doi.org/10.1111/1477-8947.12197.

Aversa D, **Adamashvili N**, **Fiore M and Spada A** (2022) Scoping review (SR) via text data mining on water scarcity and climate change. *Sustainability*, **15** (1), 70. https://doi.org/10.3390/su15010070.

Ayt Ougougdal H, **Yacoubi KM**, **Messouli M and Lachir A** (2020) Assessment of future water demand and supply under IPCC climate change and socio-economic scenarios, using a combination of models in Ourika watershed, high atlas, Morocco. *Water*, **12** (6), 1751. https://doi.org/10.3390/w12061751.

Azorin PR,and Garcia JG (2020) The productive, economic, and social efficiency of vineyards using combined drought-tolerant rootstocks and efficient low water volume deficit irrigation techniques under mediterranean semiarid conditions. *Sustainability*, **12** (5), 1930. https://doi.org/10.3390/su12051930.

Barkunan S, **Bhanumathi V and Balakrishnan V** (2020) Automatic irrigation system with rain fall detection in agricultural field. *Measurement* **156**, 107552. https://doi.org/10.1016/j.measurement.2020.107552.

Barkunan S, **Bhanumathi V and Sethuram J** (2019) Smart sensor for automatic drip irrigation system for paddy cultivation. *Computers & Electrical Engineering* **73**, 180–193. https://doi.org/10.1016/j.compeleceng.2018.11.013.

Barragan J, **Cots L**, **Monserrat J**, **Lopez R and Wu IP** (2010) Water distribution uniformity and scheduling in micro-irrigation systems for water saving and environmental protection. *Biosystems Engineering* **107** (3), 202–211. https://doi.org/10.1016/j.biosystemseng.2010.07.009.

Basu M and Shaw R (2014) Water scarcity and migration: An Indian perspective. In Md. Anwarul Abedin, Umma Habiba, Rajib Shaw, *Water Insecurity: A Social Dilemma (Community, Environment and Disaster Risk Management)*, vol. **13**. Leeds: Emerald Group Publishing Limited, pp. 187–211. https://doi.org/10.1108/S2040-7262(2013)0000013015.

Bensen D (2022) How does population growth affect water scarcity? *Healing Waters International*. Available at https://healingwaters.org/how-does-population-growth-affectwaterscarcity/#:~:text=Population%20growth%20doesn't%20just,than%20it%20can%20be%20replenished.https://healingwaters.org/how-does-population-growth-affect-waterscarcity/#:~:text=Population%20growth%20doesn't%20just,than%20it%20can%20be%20replenished (accessed 21 April 2023).

Bera S (2017) Sugar production to be 15% lower during 2016–17 due to drought. *Mint*. Available at https://www.livemint.com/Politics/uV37CIkh7O0olsT5phpE9N/Sugar-output-likely-to-be-down-by-9-as-drought-hits-cane-su.html.https://www.livemint.com/Politics/uV37CIkh7O0olsT5phpE9N/Sugar-output-likely-to-be-down-by-9-as-drought-hits-cane-su.html (accessed 15 April 2023).

Bhat TA (2014) An analysis of demand and supply of water in India. *Journal of Environment and Earth Science*, **4** (11), 67–72.

Bhogal S, **Gree AS**, **Petrie CA and Dixit S** (2022) Here's how one ancient crop is helping to fight India's water and food crisis. *World Economic Forum*. Available at https://www.weforum.org/agenda/2022/05/ancient-crop-india-water-food-crisis/ (accessed 15 April 2023).

Bodunde O, **Adie U**, **Ikumapayi O**, **Akinyoola J and Aderoba A** (2019) Architectural design and performance evaluation of a ZigBee technology based adaptive sprinkler irrigation robot. *Computers and Electronics in Agriculture*, **160**, 168–178. https://doi.org/10.1016/j.compag.2019.03.021.

Boelens R, **Hoogesteger J**, **Swyngedouw E**, **Vos J and Wester P** (2016). Hydrosocial territories: a political ecology perspective. *Water International*, **41**(1), 1–14. https://doi.org/10.1080/02508060.2016.1134898.

Bond NR, **Burrows RM**, **Kennard MJ and Bunn SE** (2019) Water scarcity as a driver of multiple stressor effects. In Sabater SS, Elosegi A and Ludwig R (eds). *Multiple Stressors in River Ecosystems*. Amsterdam, the Netherlands: Elsevier, pp. 111–129. https://doi.org/10.1016/B978-0-12-811713-2.00006-6.

Buchholz FL and Graham AT (1998) *The Structure and Properties of Superabsorbent Polyacrylates. Modern Superabsorbent Polymer Technology*. New York, NY: Wiley-VCH.

Cai J, **Varis O and Yin H** (2017) China's water resources vulnerability: a spatio-temporal analysis during 2003–2013. *Journal of Cleaner Production*, **142**, 2901–2910. https://doi.org/10.1016/j.jclepro.2016.10.180.

Cakir R (2004) Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research*, **89** (1), 1–16. https://doi.org/10.1016/j.fcr.2004.01.005.

Campisano A, **Butler D**, **Ward S**, **Burns MJ**, **Friedler E**, **DeBusk K**, **Fisher-Jeffes LN**, **Ghisi E**, **Rahman A**, **Furumai H and Han M** (2017) Urban rainwater harvesting systems: research, implementation and future perspectives. *Water Research* **115**, 195–209. https://doi.org/10.1016/j.watres.2017.02.056.

Carrington D (2016) Four billion people face severe water scarcity, new research finds. *The Guardian*. Available at https://www.theguardian.com/environment/2016/feb/12/four-billion-people-face-severe-water-scarcity-new-research finds?utm_source=inshorts&utm_medium=inshorts_full_article&utm_campaign=inshorts_full_article.https://www.theguardian.com/environment/2016/feb/12/four-billion-people-face-severe-water-scarcity-new-research-finds?utm_source=inshorts&utm_medium=inshorts_full_article&utm_campaign=inshorts_full_article (accessed 17 April 2023).

Central Water commission (2017) Reassessment of water availability in India using space inputs. *India Environment Portal knowledge for change*. Available at http://www.indiaenvironmentportal.org.in/content/449985/reassessment-of-water-availability-in-india-using-space-inputs/ (accessed 17 April 2023).

Chakkaravarthy N and Balakrishnan T (2019) Water scarcity- challenging the future. *International Journal of agriculture, environment and Biotechnology*, **12** (3), 187–193. https://doi.org/10.30954/0974-1712.06.2019.

Chakraborty D, **Nagarajan S**, **Aggarwal P**, **Gupta VK**, **Tomar RK**, **Garg RN**, **Sahoo RN**, **Sarkar A**, **Chopra UK**, **Sarma KS and Kalra N** (2008) Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. *Agricultural Water Management*, **95** (12), 1323–1334.

Chartzoulakis K and Bertaki M (2015) Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia*, **4**, 88–98. https://doi.org/10.1016/j.aaspro.2015.03.011.

Clarke B, **Otto F**, **Smith RS and Harrington L** (2022) Extreme weather impacts of climate change: an attribution perspective. *Environmental Research Climate*, **1**, 012001. https://doi.org/10.1088/2752-5295/ac6e7d.

Conservation Biology Institute (2023). Data Basin. Available at https://databasin.org/maps/new/#datasets (accessed May 2023).

Cruz JCD, **Caya MVC**, **Ballado AH**, **Aggabao MCR**, **Bacolor EI**, **Riego HAGG and Vergara MEM** (2020) Evapotranspiration-based irrigation system for mustard green crop cultivation using public weather forecast. In *2020 11th IEEE Control and System Graduate Research Colloquium (ICSGRC)*, Shah Alam, Malaysia, pp. 203–208, doi: 10.1109/ICSGRC49013.2020.9232454.

Cusser S, **Jha S**, **Lonsdorf E and Ricketts T** (2023) Public and private economic benefits of adopting conservation tillage for cotton pollination. *Agriculture, Ecosystems & Environment*, **342**, 108251. https://doi.org/10.1016/j.agee.2022.108251.

D'Odorico P, **Chiarelli DD**, **Rosa L**, **Bini A**, **Zilberman D and Rulli MC** (2020) The global value of water in agriculture. *PNAS*, **117** (36), 21985–21993. https://doi.org/10.1073/pnas.2005835117.

Damkjaer S and Taylor R (2017) The measurement of water scarcity: definition a meaningful indicator. *Ambio*, **46**, 513–531. https://doi.org/10.1007/s13280-017-0912-z.

Das S, **Chapman S**, **Christopher J**, **Choudhury MR**, **Menzies NW**, **Apan A**, **and Dang YP** (2021) UAV-thermal imaging: a technological breakthrough for monitoring and quantifying crop abiotic stress to help sustain productivity on sodic soils – a case review on wheat, *Remote Sensing Applications: Society and Environment*, **23**, 100583. https://doi.org/10.1016/j.rsase.2021.100583.

Das S, **Christopher J**, **Apan A**, **Choudhury MR**, **Chapman S**, **Menzies NW and Dang Y P** (2020) UAV-thermal imaging: a robust technology to evaluate in-field crop water stress and yield variation of wheat genotypes. *IEEE India Geoscience and Remote Sensing Symposium (InGARSS), Ahmedabad, India, 1-4 December 2020*. Piscataway, NJ, United States: IEEE, pp. 138–141. https://doi.org/10.1109/InGARSS48198.2020.9358955.

Das S, **Christopher J**, **Choudhury MR**, **Apan A**, **Chapman S**, **Menzies NW and Dang YP** (2022) Evaluation of drought tolerance of wheat genotypes in rainfed sodic soil environments using high-resolution UAV remote sensing techniques. *Biosystems Engineering*, **217**, 68–82. https://doi.org/10.1016/j.biosystemseng.2022.03.004.

Dell'Angelo J, **Rulli MC and D'Odorico P** (2018) The global water grabbing syndrome. *Ecological Economics*. **143**, 276–285. https://doi.org/10.1016/j.ecolecon.2017.06.033.

Denchak M (2023) Water pollution: everything you need to know. *NRDC. Available at https://www.nrdc.org/stories/water-pollution-everything-you-need-know#whatis (accessed 14 April 2023).*

Department of Economics and Social Affairs, Population Division (2017) *World Population Prospects: Key Findings and Advance Tables*. New York, NY: United Nations General Assembly.

Djaman K, **O'Neill M**, **Owen CK**, **Smeal D**, **Koudahe K**, **West M**, **Allen S**, **Lombard K and Irmak S** (2018) Crop evapotranspiration, irrigation water requirement and water productivity of maize from meteorological data under semiarid climate. *Water*, **10** (4), 405. https://doi.org/10.3390/w10040405.

Dobbs NA, **Migliaccio KW**, **Li Y**, **Dukes MD and Morgan KT** (2014) Evaluating irrigation applied and nitrogen leached using different smart irrigation technologies on bahiagrass (Paspalum notatum). *Irrigation Science*, **32** (3), 193–203. https://doi.org/10.1007/s00271-013-0421-1.

Dormido H (2019) These countries are the most at risk from a water crisis. *Bloomberg*. Available at https://www.bloomberg.com/graphics/2019-countries-facing-water-crisis/?leadSource=uverify%20wall (accessed 14 April 2023).

du Plessis A (2019) Current and future water scarcity and stress. In *Water as an Inescapable Risk*. Springer Water, Springer: Cham, pp. 13–25. https://doi.org/10.1007/978-3-030-03186-2_2.

Dubbudu R (2016) Per capita water availability down 70% in 60 years. *Factly*. Available at https://factly.in/per-capita-water-availability-down-70-in-60-years/ (accessed 2023).

Eikhof RH, **King PA and Koevn G** (1994) Control of wilting in potted plants. *Ohio Florists Association*, **532**, 6–7.

Emile R, **Clammer JR**, **Jayaswal P and Sharma P** (2022). Addressing water scarcity in developing contexts: A socio-cultural approach. *Humanities & Social Sciences Communications*. **9**:144. https://doi.org/10.1057/s41599-022-01140-5.

Enriquez Y, **Yadav S**, **Evangelista GK**, **Villanueva D**, **Burac MA and Pede V** (2021) Disentangling challenges to scaling alternate wetting and drying technology for rice cultivation: distilling lessons from 20 years of experience in the Philippines. *Frontiers in Sustainable Food Systems*, **5**, 675818. https://doi.org/10.3389/fsufs.2021.675818.

Erickson J (2021) Indian agriculture: Groundwater depletion could reduce winter cropped acreage significantly in years ahead. *Michigan News*. Available at https://seas.umich.edu/news/indian-agriculture-groundwater-depletion-could-reduce-winter-cropped-acreage-significantly (accessed on 14 April 2023).

European Commission (2019) The EU Water Framework Directive – integrated river basin management for Europe. Available at https://ec.europa.eu/environment/water/water-framework/index_en.html (accessed 1 October 2024).

Evans RG, **Wu IP and Smajstrala AG** (2007) Microirrigation systems. In *Design and Operation of Farm Irrigation Systems*, 2nd Edn [Hoffman, GL, Evans, RG, Jensen, ME, Martin, DL, Elliott, RL, (eds.)]. American Society of Agricultural and Biological Engineers, St. Joseph, MI, USA. pp. 632–683. https://elibrary.asabe.org/abstract.asp?aid=23700.

Famiglietti JS (2014) The global groundwater crisis. *Nature Climate Change*, **4**(11), 945–948. https://doi.org/10.1038/nclimate2425.

Feng Q, **Flanagan, DC**, **Engel BA**, **Yang L and Chen L** (2020) GeoAPEXOL, a web GIS interface for the agricultural policy environmental eXtender (APEX) model enabling both field and small watershed simulation. *Environmental Modelling & Software*, **123**, 104569. https://doi.org/10.1016/j.envsoft.2019.104569.

Food and Agriculture Organization (2020) Understanding water scarcity FAO. Physical water scarcity occurs when water to meet all demands. Economic water scarcity is caused, places where water is abundant. Available at http://www.fao.org/resources/infographics/infographics-details/en/c/218939/# (accessed 2023).

Food and Agriculture Organization of the United Nations (2003) Review of world water resources by country. Water reports 23, Rome, Italy.

Foresight (2011) The future of food and farming. Final Project Report. The Government Office for Science, London.

Friedl MA (2018) Remote sensing of croplands. In S Liang (ed.). *Comprehensive Remote Sensing*. 6, Elsevier, pp. 78–95. https://doi.org/10.1016/B978-0-12-409548-9.10379-3.

Fuentes-Llanillo R, **Telles TS**, **Junior DS**, **Melo TRD**, **Friedrich T and Kassam A** (2021) Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil and Tillage Research*, **208**, 104877. https://doi.org/10.1016/j.still.2020.104877.

Gajri PR, **Arora VK**, **Chaudhary MR and Kumar A** (2013) Evaluation of conservation tillage practices for improving productivity and water use efficiency of irrigated cotton (*Gossypium hirsutum* L.) in North Gujarat. *Indian Journal of Agricultural Sciences*, **83** (8), 837–843.

Gassman PW, **Williams JR**, **Wang X**, **Saleh A**, **Osei E**, **Hauck LM**, **Izaurralde RC and Flowers, J D** (2010). The agricultural policy environmental extender (APEX) model: an emerging tool for landscape and watershed environmental analyses. *Transactions of the ASABE*, **53**(3), 711–740. https://doi.org/10.13031/2013.30078.

Gehring JM and Lewis AJ (1980) Effect of hydrogel on wilting and moisture stress of bedding plants. *Journal of American Society of Horticultural Science*, **105** (4), 511–513.

Giller KE, **Corbeels M**, **Nyamangara J**, **Triomphe B**, **Affholder F**, **Scopel E and Tittonell P** (2011) A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field Crops Research*, **124** (3), 468–472. https://doi.org/10.1016/j.fcr.2011.04.010.

Giordano M, **Barron J and Unver O** (2019) Water scarcity and challenges for smallholder agriculture. In Campanhola C and Pandey S (eds), *Sustainable*

Food and Agriculture: An Integrated Approach. Academic Press, USA. 75–94. https://doi.org/10.1016/C2016-0-01212-3.
Gosain AK, **Rao S and Basuroy D** (2006) Climate change impact assessment on hydrology of Indian river basin. *Current Science*, **90** (3), 346–353.
Govaerts B, **Verhulst N**, **Castellanos-Navarrete A**, **Sayre KD**, **Dixon J and Dendooven L** (2009) Conservation agriculture and soil carbon sequestration: Between myth and farmer reality. *Critical Reviews in Plant Sciences*, **28** (3), 97–122. https://doi.org/10.1080/07352680902776358.
Grabow G, **Ghali I**, **Huffman R**, **Miller G**, **Bowman D and Vasanth A** (2013) Water application efficiency and adequacy of ET-based and soil moisture–based irrigation controllers for turf grass irrigation. *Journal of Irrigation and Drainage Engineering*, **139**, 113–123. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000528.
Grafton RQ and Horne J (2014) Water markets in the Murray-Darling basin. *Agricultural Water Management*, **145**, 61–71. https://doi.org/10.1016/j.agwat.2013.12.001.
Grafton RQ, **Libecap GD**, **Edwards EC**, **O'Brien RJ and Landry C** (2012) Comparative assessment of water markets: Insights from the Murray-Darling basin of Australia and the Western USA. *Water Policy*, **14** (2), 175–193. https://doi.org/10.2166/wp.2011.016.
Gupta J, **Narain V**, **Arora V and Singh A** (2021) Water scarcity and crop productivity in South Asia: a dynamic general equilibrium analysis. *Global Environmental Change*, **67**, 102209.
Guram FVS (2022) Climate changes drives down yields and nutrition of Indian crops. *The third Pole*. Available at https://www.thethirdpole.net/en/food/climate-change-drives-down-yields-and-nutrition-of-indian-crops/ (accessed 14 April 2023).
Haq Z (2023) *Farmers switch crops amid concerns over climate crisis. Hindustan Times*. Available at https://www.hindustantimes.com/cities/delhi-news/farmers-switch-crops-amid-concerns-over-climate-crisis-101678645925094 (accessed on 14 April 2023).
Harbaugh AW (2005) MODFLOW-2005: the U.S. Geological Survey modular ground-water model – the ground-water flow process. Techniques and Methods 6-A16, USGS. https://doi.org/10.3133/tm6A16.
Hatfield JL, **Boote KJ**, **Kimball BA**, **Ziska LH**, **Izaurralde RC**, **Ort D**, **Thomson AM and Wolfe D** (2011) Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, **103** (2), 351–370. https://doi.org/10.2134/agronj2010.0303.
He C, **Liu Z**, **Wu J**, **Pan X**, **Fang Z**, **Li J and Bryan BA** (2021) Future global urban water scarcity and potential solutions. *Nature Communications*, **12**(1), 4667. https://doi.org/10.1038/s41467-021-25026-3.
Helalita A and Letey J (1989) Effects of different polymers on seedling emergence, aggregate stability and crust hardness. *Soil Science*, **148** (3), 199–203. https://doi.org/10.1016/B978-0-12-811713-2.00006-6.
Hillel D (1997) Small-scale irrigation for arid zones: principles and options. *Food and Agriculture Organization*, **2**, 69.
Hughes JD, **Langevin CD and Banta ER** (2017) Documentation for the MODFLOW 6 framework. Techniques and Methods 6-A57, USGS. https://doi.org/10.3133/tm6A57.
Huitema D, **Mostert E**, **Egas W**, **Moellenkamp S**, **Pahl-Wostl C and Yalcin R** (2009) Adaptive water governance: assessing the institutional prescriptions of adaptive (co-) management from a governance perspective and defining a research agenda. *Ecology and Society*, **14**(1), 26.
Hussain Z, **Wang Z**, **Wang J**, **Yang H**, **Arfan M**, **Hassan D**, **Wang W**, **Azam MI and Faisal M** (2022) A comparative appraisal of classical and holistic water scarcity indicators. *Water Resources Management* **36**, 931–950.
Ingrao C, **Strippoli R**, **Lagioia G and Huisingh D** (2023). Water scarcity in agriculture: an overview of causes, impacts and approaches for reducing the risks. *Heliyon*, **9**, e-18507. https://doi.org/10.1016/j.heliyon.2023.e18507.
Irannezhad M, **Ahmadi B**, **Liu J**, **Chen D and Matthews JH** (2022). Global water security: a shining star in the dark sky of achieving the sustainable development goals. *Sustainable Horizons*, **1**, 100005. https://doi.org/10.1016/j.horiz.2021.100005.
Isik MF, **Sönmez Y**, **Yılmaz C**, **Özdemir V and Yılmaz E N** (2017) Precision irrigation system (PIS) using sensor network technology integrated with IOS/android application. *Applied Sciences*, **7** (9), 891. https://doi.org/10.3390/ app7090891.
Islam SMF and Karim Z (2020) World's demand for food and water: the consequences of climate change. In Farahani MHDA, Vatanpour V and Taheri A (eds), *Desalination- Challenges and Opportunities*. IntechOpen, London, UK. pp. 1–27 https://doi.org/10.5772/intechopen.85919.
IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A:Global and Sectoral Aspects. *Contribution of Working Group II to the FifthAssessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir,M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N., Levy, S., MacCracken, , P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge UniversityPress, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
Jain N (2018) India's groundwater crisis, fueled by intense pumping, needs urgent management. *MONGABAY*. Available at https://india.mongabay.com/2018/06/indias-groundwater-crisis-fueled-by-intense-pumping-needs-urgent-management/ (Accessed 11 April 2023).
Jat RA, **Sahrawat Kassam AG and Friedrich T** (2013) Conservation Agriculture for Sustainable and Resilient Agriculture: Global Status, Prospects and Challenges, In *Conservation Agriculture: Global Prospects and Challenges*[Jat, RA, Sahrawat KL and Kassam AH (eds)], CABI International, Wallingford, Oxfordshire, UK. pp. 1–25. DOI:10.1079/9781780642598.0001
Jensen ME (1993) The impacts of irrigation and drainage on the environment. 5th Gulhati Memorial Lecture. 15th ICID Congress, The Hague, ICID, New Delhi. Available at https://www.icid.org/awards_nd.html (accessed 2023).
Johnson H, **South N and Walters R** (2016). The commodification and exploitation of fresh water: property, human rights and green criminology. *International Journal of Law Crime and Justice*, **44**, 146–162. https://doi.org/10.1016/j.ijlcj.2015.07.003.
Kader MA, **Senge M**, **Mojid MA and Ito K** (2017) Recent advances in mulching materials and methods for modifying soil environment. *Soil Tillage Research*, **168** (5), 155–166. https://doi.org/10.1016/j.still.2017.01.001.
Kapuria P and Banerjee S (2022) Crop shifting for improved water use and nutritional productivity in the lower Indo-Gangetic plains of West Bengal. Observer Research Foundation. ORF Occasional paper no.358, New Delhi, India.
Kaur R and Jat RK (2017) Conservation tillage: a potential strategy for sustainable agriculture in the indo-Gangetic Plains. *Current Science*, **112** (1), 21–27.
Kerlin K (2015) Drought costs California agriculture $1.84B and 10,100 jobs in 2015. *UC Davis*. Available at https://www.ucdavis.edu/news/drought-costs-california-agriculture-184b-and-10100-jobs-2015 (accessed 2023).
Khandoker S, **Miah MAM**, **Khatun M**, **Hoq MS and Kundu ND** (2014) Impact of shifting of land under cereal crops to jujube cultivation in selected areas of Bangladesh. *Bangladesh Journal of Agricultural Research*, **39** (2), 243–262. https://doi.org/10.3329/bjar.v39i2.20427.
Kim Y, **Han M**, **Kabubi J**, **Sohn HG and Nguyen DC** (2016) Community-based rainwater harvesting (CB-RWH) to supply drinking water in developing countries: lessons learned from case studies in Africa and Asia. *Water Supply*, **16**, 1110–1121.
Kresović B, **Tapanarova A**, **Tomić Z**, **Životić L**, **Vujović D**, **Sredojević Z and Gajić B** (2016) Grain yield and water use efficiency of maize as influenced by different irrigation regimes through sprinkler irrigation under temperate climate. *Agricultural Water Management*, **169**, 34–43. https://doi.org/10.1016/j.agwat.2016.01.023.
Krishnan RS, **Julie EG**, **Robinson YH**, **Raja S**, **Kumar R and Thong PH** (2020) Fuzzy logic based smart irrigation system using internet of things. *Journal of Cleaner Production*, **252**, 119902. https://doi.org/10.1016/j.jclepro.2019.119902.
Kumar SS, **Bibin C**, **Akash K**, **Aravindan K**, **Kishore M and Magesh G** (2020). Solar powered water pumping systems for irrigation: a comprehensive review in developments and prospects towards a green energy approach. *Materials Today: Proceedings* **33**(1), 303–307. https://doi.org/10.1016/j.matpr.2020.04.092.
Kaur A, **Bhatt DP and Raja L** (2024) Developing a Hybrid Irrigation System for Smart Agriculture Using IoT Sensors and Machine Learning in Sri Ganganagar, Rajasthan. *Journal of Sensors*, **6676907**, p.15. https://doi.org/10.1155/2024/6676907
Lai O (2022) Water shortage: causes and effect. *EARTH.ORG*. Available at https://earth.org/causes-and-effects-of-water-shortage/.https://earth.org/causes-and-effects-of-water-shortage/ (accessed 12 April 2023).
Lakmeeharan K, **Manji Q**, **Nyairo R and Poeltner H** (2020) *Solving Africa's Infrastructure Paradox*. New York, NY: McKinsey & Company. Available

at https://www.mckinsey.com/business-functions/operations/our-insights/solving-africasinfrastructure-paradox (accessed 2023).

Langevin CD, Thorne DT, Dausman AM, Sukop MC and Guo W (2008) SEAWAT version 4: a computer program for simulation of multi-species solute and heat transport. Techniques and Methods 6-A22. USGS, p. 39. https://doi.org/10.3133/tm6A22.

Lauren JG, Shrestha R, Sattar MA and Yadav RL (2008) Legumes and diversification of the rice-wheat cropping system. *Journal of Crop Production*, **3** (2), 67–102. https://doi.org/10.1300/J144v03n02_04.

Li R, Hou X, Jia Z, Han Q, Ren X and Yang B (2013) Effects on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the loess plateau, China. *Agricultural Water Management*, **116**, 101–109. https://doi.org/10.1016/j.agwat.2012.10.001.

Liao R, Zhang S, Zhang X, Wang M, Wu H and Zhangzhong L (2021) Development of smart irrigation systems based on real-time soil moisture data in a greenhouse: proof of concept. *Agricultural Water Management*, **245**, 106632. https://doi.org/10.1016/j.agwat.2020.106632.

Liu W, Liu X, Yang H, Ciais P and Wada Y (2022) Global water scarcity assessment incorporating green water in crop production. *Water Resources Research*, **58** (1), e2020WR028570. https://doi.org/10.1029/2020wr028570.

Loch A and Adamson D (2015) Drought and the rebound effect: a Murray–Darling basin example. *Natural Hazards*, **79**, 1429–1449. https://doi.org/10.1007/s11069-015-1705-y.

Luo L, Mei H, Yu X, Xia H, Chen L, Liu H and Li M (2019) Water-saving and drought-resistance rice: from the concept to practice and theory. *Molecular Breeding*, **39** (11), 1–15. https://doi.org/10.1007/s11032-019-1057-5.

Ma Y, Zhang L, Song S and Yu S (2022) Impacts of energy Price on agricultural production, energy consumption, and carbon emission in China: a price endogenous partial equilibrium model analysis. *Sustainability*, **14** (5), 3002. https://doi.org/10.3390/su14053002.

Mahato A, Upadhyay S and Sharma D (2022) Global water scarcity due to climate change and its conservation strategies with special reference to India: a review. *Plant Archives*, **22** (1), 64–69. https://doi.org/10.51470/PLANTARCHIVES.2022.v22.no1.009.

Malone B, Biggins D, Sharman C, Searle R, Glover M and Brown S (2024) An experiential account with recommendations for the design, installation, operation and maintenance of a farm-scale soil moisture sensing and mapping system. *Soil Research*, **62**, SR24004. https://doi.org/10.1071/SR24004.

Mancini L, Benini L and Sala S (2016) Characterization of raw materials based on supply risk indicators for Europe. *The International Journal of Life Cycle Assessment*, **23**, 726–738. https://doi.org/10.1007/s11367-016-1137-2.

Mancosu N, Snyder R L, Kyriakakis G and Spano D (2015) Water scarcity and future challenges for food production. *Water*, **7**, 975–992. https://doi.org/10.3390/w7030975.

Mansour HA, Abdelghani SS, Aljughaiman AS and Saad SS (2020) Economic evaluation of subsurface drip irrigation pipe fitting machine. *Plant Archives*, **20** (1), 3565–3572.

Marengo JA, Galdos MV, Challinor A, Cunha AP, Marin FR, Vianna MDS, Alvala RCS, Alves LM, Moraes OL and Bender F (2022) Drought in Northeast Brazil: a review of agricultural and policy adaptation options for food security. *Climate Resilience and Sustainability*, **1** (1), e17. https://doi.org/10.1002/cli2.17.

Martey E, Etwire PM and Kuwornu JKM (2020) Economic impacts of smallholder farmers' adoption of drought-tolerant maize varieties. *Land Use Policy*, **94**, 104524. https://doi.org/10.1016/j.landusepol.2020.104524.

McCready M, Dukes MD and Miller G (2009) Water conservation potential of smart irrigation controllers on St. Augustine grass. *Agricultural Water Management*, **96** (11), 1623–1632. https://doi.org/10.1016/j.agwat.2009.06.007.

Mekonnen MM, Hoekstra AY, Alemu MH and Ghezehei SB (2020) Mitigating the impact of water scarcity on agriculture in the Mediterranean region. *Nature Sustainability*, **3** (12), 1072–1079.

Mendonça S R, Ávila MCR, Vital RG, Evangelista ZR, Pontes NDC and Nascimento ADR (2021) The effect of different mulching on tomato development and yield. *Scientia Horticulturae*, **275**, 109657. https://doi.org/10.1016/j.scienta.2020.109657.

Migliaccio KW, Schaffer B, Crane JH and Davies FS (2010) Plant response to evapotranspiration and soil water sensor irrigation scheduling methods for papaya production in South Florida. *Agricultural Water Management*, **97** (10), 1452–1460. https://doi.org/10.1016/j.agwat.2010.04.012.

Minenna M and Aversa D (2019) A revised European stability mechanism to realize risk sharing on public debts at market conditions and realign economic cycles in the euro area. *Economic Notes: Review of Banking, Finance and Monetary Economics*, **48** (1), 12118. https://doi.org/10.1111/ecno.12118.

Ministry of Water Resources (2000) *Annual Report 1999–2000*. Government of India: New Delhi.

Mirdashtvan M, Najafinejad A, Malekian A and Sa'doddin A (2021) Sustainable water supply and demand management in semi-arid regions: optimizing water resources allocation based on RCPs scenarios. *Water Resources Management*, **35**, 5307–5324. https://doi.org/10.1007/s11269-021-03004-0.

Mishra RK (2023). Fresh water availability and its global challenge. *British Journal of Multidisciplinary and Advanced Studies*, **4**(3), 1–78. https://doi.org/10.37745/bjmas.2022.0208.

Mohan V (2023) How serious is India's water crisis? *The Times of India.* Available at https://timesofindia.indiatimes.com/india/how-serious-is-indias-water-crisis/articleshow/98887141.cms (accessed 16 April 2023).

Molden D (2013) *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Routledge, London. https://doi.org/10.4324/9781849773799.

Molle F and Closas A (2020) Why is state-centered groundwater governance largely ineffective? A review. *WIREs Water*, **7** (1), e1395. https://doi.org/10.1002/wat2.1395.

Mukherjee B (2022) Effect of sowing time, tillage and variety on lentil and chickpea after monsoon rice in New Alluvial Zone of West Bengal. Ph.D. (Ag.) Thesis. Department of Agronomy, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal, India.

NITI Aayog (2019) *Composite Water Management Index*. New Delhi, India: Ministry of Jal Shakti and Ministry of Rural Development.

Nnadi F and Brave C (2011) Environmentally friendly superabsorbent polymers for water conservation in agricultural lands. *Journal of Soil Science and Environmental Management*, **2** (7), 206–211.

Odhiambo KO, Ong'or BTI and Kanda EK (2021) Optimization of rainwater harvesting system design for smallholder irrigation farmers in Kenya: a review. *AQUA—Water Infrastructure, Ecosystems and Society*, **70** (4), 483–492.

Oki T and Quiocho RE (2020) Economically challenged and water scarce: Identification of global populations most vulnerable to water crises. *International Journal of Water Resources Development* **36**(2–3), 416–428.

Ooi SK, Cooley N, Mareels I, Dunn G, Dassanayake K and Saleem K (2010) Automation of on-farm irrigation: horticultural case study. *IFAC Proceedings* **43**, 256–261. https://doi.org/10.3182/20101206-3-JP-3009.0004.

Ostrom E (2015) *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press. United Kingdom.

Pal D, Mondal S, Banerjee S, Saha A and Pramanick M (2022) Evaluating the influence of conservation agricultural practices and fertilizer on PAR use efficiency and biophysical parameters of maize grown under new alluvial zone of West Bengal. *Journal of Agrometeorology*, **24** (2), 192–195. https://doi.org/10.54386/jam.v24i2.1548.

Panigrahi P, Raychaudhuri S, Thakur A, Nayak A, Sahu P and Ambast S (2019) Automatic drip irrigation scheduling effects on yield and water productivity of banana. *Scientia Horticulturae*, **257**, 108677. https://doi.org/10.1016/j.scienta.2019.108677.

Pereira LS, Cordery I and Iacovides I (2009) *Coping with Water Scarcity*. International Hydrological Programme. Paris, France: UNESCO. https://doi.org/10.1007/978-1-4020-9579-5_1.

Petruzzello M (2023) Water scarcity natural resource. *Britannica.* Available at https://www.britannica.com/topic/water-scarcity#ref1265085 (accessed 9 April 2023).

Postel S, Polak P, Gonzales F and Keller J (2001) Drip irrigation for small farmers – a new initiative to alleviate hunger and poverty. *Water International*, **26** (1), 3–13. https://doi.org/10.1080/02508060108686882.

Prasad R (2002) *Textbook of Field Crops Production-Foodgrain Crops*, vols. **1, 2**. New Delhi: Indian Council of Agricultural Research.

Qin S, Li S, Kang S, Du T, Tong L and Ding R (2016) Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition? *Agricultural Water Management*, **177** (C), 128–137. https://doi.org/10.1016/j.agwat.2016.06.022.

Qureshi RH and Ashraf M (2019) *Water Security Issues of Agriculture in Pakistan*. Islamabad: Pakistan Academy of Sciences. Available at https://www.paspk.org/wp-content/uploads/2019/06/PAS-Water-Security-Issues.pdf (accessed 2023).

Reghukumar A and Vijayakumar V (2019) Smart plant watering system with cloud analysis and plant health prediction. *Procedia Computer Science*, **165**, 126–135. https://doi.org/10.1016/j.procs.2020.01.08.

Rijsberman FR (2006) Water scarcity: fact or fiction?. *Agricultural Water Management*, **80**(1–3), 5–22. https://doi.org/10.1016/j.agwat.2005.07.001.

Rinkesh (2023) Causes, effects and solutions to water scarcity (water deficit). *Conservation Energy Future.* Available at https://www.conserve-energy-future.com/causes-effects-solutions-of-water-scarcity.php (accessed 2023).

Ritchie H and Roser M (2018) Water use and stress: renewable freshwater resources per capita. *Our World in Data.* Available at https://ourworldindata.org/water-use-stress (accessed 9 April 2023).

Romero P, Navarro JM and Ordaz PB (2022) Towards a sustainable viticulture: the combination of deficit irrigation strategies and agroecological practices in Mediterranean vineyards. A review and update. *Agricultural Water Management*, **259**, 107216. https://doi.org/10.1016/j.agwat.2021.107216.

Rosa L, Chiarelli DD, Rulli MC, Dell'Angelo J and D'Odorico P (2020) Global agricultural economic water scarcity. *Science Advances*, **6**(18), eaaz6031. https://doi.org/10.1126/sciadv.aaz6031.

Rosa L, Rulli MC, Davis KF, Chiarelli DD, Passera C and D'Odorico P (2018) Closing the yield gap while ensuring water sustainability. *Environmental Research Letters*, **13**(10), 104002. https://doi.org/10.1088/1748-9326/aadeef.

Rosegrant MW and Cai X (2002) Global water demand and supply projections. *Water International*, **27** (2), 170–182. https://doi.org/10.1080/02508060208686990.

Rudzinski WE, Dave AM, Vaishnav UH, Kumbar SG, Kulkarni AR and Aminabhavi TM (2002) Hydrogels as controlled release devices in agriculture. *Designed Monomers and Polymers*, **5** (1), 39–65. https://doi.org/10.1163/156855502760151580.

Rutland D and Dukes M (2012) Performance of rain delay features on signal-based evapotranspiration irrigation controllers. *Journal of Irrigation and Drainage Engineering*, **138** (11), 978–983. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000499.

Saleth RM (2011) Water scarcity and climatic change in India: the need for water demand and supply management. *Hydrological Sciences Journal*, **56** (4), 671–686. https://doi.org/10.1080/02626667.2011.572074.

Saxena CK, Ambast SK and Gupta SK (2020) Laser land levelling for higher water productivity in rice-wheat system. *International Journal of Innovative Technology and Exploring Engineering*, **9** (8), 374–379. https://doi.org/10.35940/ijitee.H6482.069820.

Schewe J, Heinke J, Gerten D, Haddeland I, Arnell N, Clark D, Dankers R, Eisner S, Fekete B, Colón-González F J, Gosling S, Kim H, Liu X, Masaki Y, Portmann F, Satoh Y, Stacke T, Tang Q, Wada, Y and Kabat P (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 3245–3250. https://doi.org/10.1073/pnas.1222460110.

Schneider K (2018) Groundwater scarcity, pollution set India om perilous course. *Circle of Blue.* Available at https://www.circleofblue.org/2018/world/groundwater-scarcity-pollution-set-india-on-perilous-course/ (accessed 2023).

Schwab K (2019) *The Global Competitiveness Report*. World Economic Forum. Available at https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2019.pdf (accessed 2023).

Seckler D, Amarasinghe U, Molden D, Silva RD and Barker R (1998) *World Water Demand and Supply, 1990 to 2025: Scenarios and Issue*. Colombo, Srilanka: International Irrigation Management Institute.

Seckler D, Barker R and Amarasinghe U (1999) Water scarcity in the twenty-first century. *International Journal of Water Resources Development*, **15**(1–2), 29–42. https://doi.org/10.1080/07900629948916.

Shah T, Ul-Hassan M, Khattak MS and Ahmad SS (2019) Impact of water scarcity on agriculture productivity: a case study of Indus Basin, Pakistan. *International Journal of Agriculture and Biology*, **23** (4), 684–690.

Shukla M, Sadhu AC, Chinchmalatpure AR, Prasad I, Kumar S and Camus D (2018) Fertigation- modern technique of fertilizer application. *Indian Farmer*, **5** (09), 1062–1071.

Singh Y, Mishra AK, Singh G, Singh SK, Sharma DK and Verma AK (2017) Conservation tillage for enhancing crop productivity and water use efficiency in Northwest India. *Journal of Cleaner Production*, **155**, 61–71.

Sojka RE and Lentz RD (1997) Reducing furrow irrigation erosion with polyacrylamide (PAM). *Journal of Production Agriculture*, **10**, 47–52. https://doi.org/10.2134/jpa1997.004710.2134/jpa1997.0047.

Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal*, **10**(1), 52–67. https://doi.org/10.1007/s10040-001-0170-8.

Srivastava M, Pawar N and Srivastava A (2023) Unlocking the vast potential of water quality data. *TOI Opinion.* Available at https://timesofindia.indiatimes.com/blogs/voices/unlocking-the-vast-potential-of-water-quality-data/.

Steduto P, Hsiao TC, Raes D and Fereres E (2009) AquaCrop—the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, **101**(3), 426–437. https://doi.org/10.2134/agronj2008.0139s.

Taylor R, Scanlon B, Doell P, Rodell M, Beek R, Wada Y, Longuevergne L, Leblanc M, Famiglietti J, Edmunds M, Konikow L, Green T, Chen J, Taniguchi M, Bierkens M F P, Macdonald A, Fan Y, Maxwell R, Yechieli Y and Treidel H (2013) Ground water and climate change, *Nature Climate Change*, **3**, 322–329. https://doi.org/10.1038/nclimate1744.

Tayyab M, Abbas Y and Hussain MW (2022) Management options for large metropolitans on the verge of a water stress. *Journal of Human, Earth, and Future* **3**(3), 333–344. https://doi.org/10.28991/HEF-2022-03-03-06.

Temple J (2019) India's water crisis is already here. Climate change will compound it. *MIT Technology Review*. Available at https://www.technologyreview.com/2019/04/24/135916/indias-water-crisis-is-already-here-climate-change-will-compound-it/ (accessed 5 April 2023).

Teyel M Y and El-Hady OA (1981) Super gel as a soil conditioner. *Acta Horticulturae*, **119**, 247–256.

Tal A. (2021) *Israeli Agriculture—Innovation and Advancement*. In: *From Food Scarcity to Surplus: Innovations in Indian, Chinese and Israeli Agriculture* [Gulati, A, Zhou, Y, Huang, J, Tal, A, and Juneja, R, (eds.)] Springer, Singapore. 299–358. https://doi.org/10.1007/978-981-15-9484-7_9.

The World Bank (2023) How is India addressing its water needs? Available at https://www.worldbank.org/en/country/india/brief/world-water-day-2022-how-india-is-addressing-its-water-needs#:~:text=The%20country%20has%2018%20percent,think%20tank%2C%20the%20NITI%20Aayog [accessed 24 April 2023).

Turner RK, Georgiou S, Clark R, Brouwer R and Burke JJ (2004) *Economic Valuation of Water Resources in Agriculture: From the Sectoral to a Functional Perspective of Natural Resource Management*, vol. **27**. Food & Agriculture Org.

UNESCO (2022) UN World Water Development Report. Available at https://www.unesco.org/reports/wwdr/2022/en/agriculture#:~:text=Summary&text=Currently%2070%25%20of%20global%20groundwater,is%20serviced%20by%20this%20resource (accessed 2023).

UNESCO Digital Library (2003) Water for People, Water for Life: The United Nations World Water Development Report; Executive summary. Available at https://unesdoc.unesco.org/ark:/48223/pf0000129556 (accessed 2023).

UNESCO, UN-Water, & World Water Assessment Programme (2012) *The United Nations World Water Development Report 4: Managing Water Report Under Uncertainty and Risk (Vol. 1), Knowledge Base (Vol. 2) and Facing the Challenges (Vol. 3).* Paris, France: UNESCO. Available at https://digitallibrary.un.org/record/3892696?ln=en.

UNESCO World Water Assessment Programme (2018) *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, France: UNESCO, p. 139.

UNESCO World Water Assessment Programme (2023) *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*. Paris, France: UNESCO, p. 189.

UNICEF (2023) Water and the global climate crisis: 10 things you should know. *UNICEF*. Available at https://www.unicef.org/stories/water-and-climate-change-10-things-you-should-know (accessed 18 April 2023).

UNICEF for every child (2017) Nearly 600 million children will live in areas with extremely limited water resources by 2030. UNICEF. https://www.unicef.org/

press-releases/nearly-600-million-children-will-live-areas-extremely-limited-water-resources-2040 (accessed 2023).

United Nations (2022) *The United Nations World Water Development Report 2022. Groundwater: Making the Invisible Visible*. Paris: UNESCO. Available at https://unesdoc.unesco.org/ark:/48223/pf0000380721 (accessed 10 September 2023).

United Nations Department of Economic and Social Affairs, Population Division (2013) *World Population Prospects: The 2012 Revision, Volume II, Demographic Profiles (ST/ESA/SER.A/345)*. New York, NY: United Nations Department of Economic and Social Affairs.

Upadhyay D (2020) Water security in India: a bigger challenge. *Readers' Blog*. Available at https://timesofindia.indiatimes.com/readersblog/sustainable-thoughts/water-security-in-india-a-bigger-challenge-22332/ (accessed 24 April 2023).

Vanham D, Hoekstra A Y, Wada Y, Bouraoui F, de Roo A, Mekonnen M M, van de Bund V J, Batelaan O, Pavelic P, Bastiaanssen W G M, Kummu M, Rockström J, Liu J, Bisselink B, Ronco P, Pistocchi A and Bidoglio G (2018) Physical water scarcity metrics for monitoring progress towards SDG target 6.4: an evaluation of indicator 6.4.2 "level of water stress". *Science of the Total Environment*, **613–614**, 218–232. https://doi.org/10.1016/j.scitotenv.2017.09.056.

Varma DS, Nandanan K, VishakhRaja PC, Soundharajan B, Pérez M L, SidharthK A and Ramesh MV (2021). Participatory design approach to address water crisis in the village of Karkatta, Jharkhand, India. *Technological Forecasting and Social Change*, **172**, 121002.

Veldkamp TIE, Wada Y, Aerts JCJH and Ward PJ (2016) Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability. *Environmental Research Letter*, **11** (2), 024006. https://doi.org/10.1088/1748-9326/11/2/024006.

Wang J, Li Y, Zhang T, Chen Y and Li X (2021) Irrigation management during the critical growth stage improves tomato yield and quality by regulating soil moisture and air temperature. *Agricultural Water Management*, **246**, 200–211.

Williams JR, Dyke PT and Jones CA (1983) EPIC: A model for assessing the effects of erosion on soil productivity. In William KL, Gaylord VS and Marshall F (eds), *Developments in Environmental Modelling (Elsevier)*, vol. **5**. pp. 553–572. https://doi.org/10.1016/B978-0-444-42179-1.50065-1.

Winschewski J (2017) Putting a price tag on human rights: an anthropological perspective on Nestle's drinking water privatisation in Pakistan. *Prace Etnograficzne* **45**(2), 175–195.

Winston RB (2022) *Getting Started with MODFLOW*. The Groundwater Project, Guelph, Ontario, Canada. https://doi.org/10.21083/978-1-77470-030-3.

Winter TC, Harvey JW, Franke OL and Alley WM (1998). Ground water and surface water: A single resource. *U.S. Geological Survey Circular 1139*, **vii**, 79. https://doi.org/10.3133/cir1139.

World Economic Forum (2015) Global Risks. Geneva, Switzerland.

World Health Organization & United Nations Children's Fund (2020) Water, sanitation, hygiene, and waste management for SARS-CoV-2, the virus that causes COVID-19: interim guidance. World Health Organization. Available at https://www.who.int/publications/i/item/water-sanitation-hygiene-and-wastemanagement-for-the-covid-19-virus-interim-guidance (accessed 12 September 2023).

World Resources Institute (2023) India Water Tool 2.0 (accessed in 2023).

Yasuor H, Yermiyahu U and Ben-Gal A (2020) Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. *Agricultural Water Management*, **242**, 106362. https://doi.org/10.1016/j.agwat.2020.106362.

Yeung J, Gupta S and Kann D (2021) India's groundwater crisis threatens food security for hundreds of millions, study says. *CNN*. Available at https://edition.cnn.com/2021/02/24/asia/india-groundwater-study-intl-hnk-scn/index.html (accessed 20 April 2023).

Yokoyama S, Kajisab K and Miyazaki T (2011) Social experiment of volumetric irrigation fee scheme: case of gravity irrigation system in Bohol, the Philippines. In Proceedings of the 7th Asian Crop Science Association Conference, Bogor, West Java, Indonesia. Available at https://repository.ipb.ac.id/jspui/bitstream/123456789/62169/26/ACSACISBN-27.pdf (accessed 2023).

Zamani O, Azadi H, Mortazavi SA, Balali H, Moghaddam SM and Jurík L (2020) The impact of water-pricing policies on water productivity: evidence of agriculture sector in Iran. *Agricultural Water Management*, **245**, 106548. https://doi.org/10.1016/j.agwat.2020.106548.

Zhang D, Liu HB, Hu WL, Qin XH, Yan CR and Wang HY (2016) The status and distribution characteristics of residual mulching film in Xinjiang, China. *Journal of Integrative Agriculture*, **15** (11), 2639–2646. https://doi.org/10.1016/S2095-3119(15)61240-0.

Zhang X, Wang D, Chen D, Wang M and Wu F (2021) Global food production could be at risk due to water scarcity under climate change. *Environmental Research Letters*, **16** (3), 034015.

Zhang X, Zhang J, Li L, Zhang Y and Yang G (2017) Monitoring citrus soil moisture and nutrients using an IoT based system. *Sensors*, **17** (3), 447. https://doi.org/10.3390/ s17030447.

Zheng C and Wang PP (1999) MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide (Accession Number: ADA373474. USGS. p. 219.

Zisopoulou K and Panagoulia D (2021) An in-depth analysis of physical blue and green water scarcity in agriculture in terms of causes and events and perceived amenability to economic interpretation. *Water*, **13**, 1693. https://doi.org/10.3390/w13121693.

Zribi W, Aragüés R, Medina E and Faci JM (2015) Efficiency of inorganic and organic mulching materials for soil evaporation control. *Soil Tillage Research*, **148**, 40–45. https://doi.org/10.1016/j.still.2014.12.003.