Water Science and Technology Library

Basant Yadav · Mohit Prakash Mohanty ·
Ashish Pandey · Vijay P. Singh ·
R. D. Singh *Editors*

Sustainability of Water Resources

Impacts and Management

Springer

Water Science and Technology Library

Volume 116

The aim of the *Water Science and Technology Library* is to provide a forum for dissemination of the state-of-the-art of topics of current interest in the area of water science and technology. This is accomplished through publication of reference books and monographs, authored or edited. Occasionally also proceedings volumes are accepted for publication in the series. *Water Science and Technology Library* encompasses a wide range of topics dealing with science as well as socio-economic aspects of water, environment, and ecology. Both the water quantity and quality issues are relevant and are embraced by *Water Science and Technology Library*. The emphasis may be on either the scientific content, or techniques of solution, or both. There is increasing emphasis these days on processes and *Water Science and Technology Library* is committed to promoting this emphasis by publishing books emphasizing scientific discussions of physical, chemical, and/or biological aspects of water resources. Likewise, current or emerging solution techniques receive high priority. Interdisciplinary coverage is encouraged. Case studies contributing to our knowledge of water science and technology are also embraced by the series. Innovative ideas and novel techniques are of particular interest.

Comments or suggestions for future volumes are welcomed.

Vijay P. Singh, Department of Biological and Agricultural Engineering & Zachry Department of Civil and Environment Engineering, Texas A&M University, USA Email: vsingh@tamu.edu

All contributions to an edited volume should undergo standard peer review to ensure high scientific quality, while monographs should also be reviewed by at least two experts in the field.

Manuscripts that have undergone successful review should then be prepared according to the Publisher's guidelines manuscripts: https://www.springer.com/gp/authors-editors/book-authors-editors/book-manuscript-guidelines

Basant Yadav · Mohit Prakash Mohanty ·
Ashish Pandey · Vijay P. Singh · R. D. Singh
Editors

Sustainability of Water Resources

Impacts and Management

Springer

Editors
Basant Yadav
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India

Mohit Prakash Mohanty
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India

Ashish Pandey
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India

Vijay P. Singh
Department of Biological and Agricultural
Engineering
Texas A&M University
College Station, TX, USA

R. D. Singh
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India

ISSN 0921-092X ISSN 1872-4663 (electronic)
Water Science and Technology Library
ISBN 978-3-031-13466-1 ISBN 978-3-031-13467-8 (eBook)
https://doi.org/10.1007/978-3-031-13467-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Editors and Contributors

About the Editors

Dr. Basant Yadav is Assistant Professor at the Department of Water Resource Development and Management, Indian Institute of Technology Roorkee, India. His areas of interest are groundwater and contaminant hydrology, Water quality, Optimal remediation system design, Artificial Recharge, Rainwater harvesting, Conjunctive water use planning, Managed Aquifer Recharge (MAR) and its impacts on groundwater quantity and quality, Integration of experimental, numerical, and data-based modeling in groundwater management studies. Prof. Yadav was awarded the "Rien van Genuchten Early-Career award of Porous Media for a Green World" by the International Society for Porous Media (InterPore) for his work in the area of porous media.

Mohit Prakash Mohanty is currently working as Assistant Professor at the Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee. His area of research is flood risk management, flood hazard mapping, vulnerability analysis, climate change impact assessment, population exposure, flood resilience mechanisms, hydrological modeling, design rainfall analysis for data-poor catchments, statistical downscaling, water and wastewater treatment, and bio-kinetics modeling for pollutant removal.

Prof. Ashish Pandey has a Ph.D. in Soil and Water Conservation Engineering and works in the area of irrigation water management, micro-irrigation, OFD works, soil and water conservation engineering, watershed modeling, remote sensing and GIS applications, and water resources. He has completed nine sponsored R&D projects, and seven R&D projects are ongoing which have been sponsored by various organizations.

Prof. Vijay P. Singh is University Distinguished Professor, Regents Professor, and Caroline and William N. Lehrer Distinguished Chair in Water Engineering at Texas

A&M University, USA. He was recently elected to the National Academy of Engineering class of 2022 for his wave modeling and entropy-based hydrologic and hydroclimatic theories. He has been awarded three honorary doctorates: the Ven Te Chow Award, the Merriam Improved Irrigation Award, and the Arid Lands Hydraulic Engineering Award. He is Member of 12 science/engineering academies. He has written around 1450 academic articles, 35 textbooks, 85 edited reference books, 120 chapters, and 330 conference papers. He is on the editorial boards of the Journal of Hydraulic Engineering, Water Science and Engineering and Journal of Groundwater Research, Irrigation Science, and Hydrologic Processes. His specialities include water quality, water resources, entropy theory, and copula theory.

Dr. R. D. Singh has experience of working as Scientist at National Institute of Hydrology, Roorkee, for about 25 years, and retired as Director, National Institute of Hydrology, Roorkee. He has also worked as Adjunct Faculty and is presently working as Visiting Professor at the Department of Water Resources Development and Management (DWRDM) at Indian Institute of Technology, Roorkee.

Contributors

Ahir P. B. Department of Agricultural and Food Engineering, IIT Kharagpur, Kharagpur, West Bengal, India

Alam Mehtab Jamia Millia Islamia, New Delhi, India

Ansari Mohd Izharuddin Jamia Millia Islamia, New Delhi, India

Bajpai Mukul Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh, India

Bandyopadhyay Arnab Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli (Itanagar), Arunachal Pradesh, India

Bansal Anjali Department of Civil Engineering, Indian Institute of Technology Delhi, Delhi, India

Barua Anamika Department of Humanities and Social Sciences, IIT Guwahati, Guwahati, Assam, India

Beker Bahar Adem Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India

Chandu Navya Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai, India

Choudhary Sourav Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India

Dayal Deen Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Devi Juna Probha Centre for the Environment, IIT Guwahati, Guwahati, Assam, India

Eldho T. I. Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai, India

Fohrer Nicola Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany

Galkate R. V. National Institute of Hydrology, Central India Regional Centre, WALMI Campus, Bhopal, Madhya Pradesh, India

Garg Rahul National Institute of Hydrology, Roorkee, Uttarakhand, India

Gaur Srishti Postdoctoral Scholar, Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Ohio, United States

Gupta Mayank Department of Civil Engineering, MNIT Jaipur, Jaipur, India

Hassan Quamrul Jamia Millia Islamia, New Delhi, India

Hatcho Nobumasa Faculty of Agriculture, Kindai University, Nakamachi, Nara, Japan

Hirofumi Okumura Rural Promotion Division, Food and Agricultural Promotion Department, Nara Prefecture, Nara, Japan

Hörmann Georg Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany

Jaiswal R. K. National Institute of Hydrology, Central India Regional Centre, WALMI Campus, Bhopal, Madhya Pradesh, India

Jat Mahesh Kumar Department of Civil Engineering, MNIT Jaipur, Jaipur, India

Kansal Mitthan Lal Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Katoch Surjit Singh Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh, India

Kebebe Tadese Gindo Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India

Khare Deepak Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India

Kimura Masaomi Faculty of Agriculture, Kindai University, Nakamachi, Nara, Japan

Krishan Gopal National Institute of Hydrology, Roorkee, Uttarakhand, India

Krishna Ch. Naga Tulasi Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India

Kumar Amit Department of Civil Engineering, MNIT Jaipur, Jaipur, India

Kumar Arun Department of Civil Engineering, Indian Institute of Technology Delhi, Delhi, India

Kumar Bhishm IAEA, Vienna, Austria;
NIH, Roorkee, India

Kumar Mohit National Institute of Hydrology, Roorkee, Uttarakhand, India

Kumar Ravi National Institute of Hydrology, Roorkee, Uttarakhand, India

Kumar Sudhir Department of Civil Engineering, MNIT Jaipur, Jaipur, India

Kumari Chanchal National Institute of Hydrology, Central India Regional Centre, WALMI Campus, Bhopal, Madhya Pradesh, India

Lohani A. K. National Institute of Hydrology, Jal Vigyan Bhavan Roorkee, Roorkee, Uttarakhand, India

Mahanta Chandan Department of Civil Engineering, IIT Guwahati, Guwahati, Assam, India

Matsuno Yutaka Faculty of Agriculture, Kindai University, Nakamachi, Nara, Japan

Mishra S. K. Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Mondal Manoj K. Rajendra Mishra School of Engineering Entrepreneurship, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India

Mrinmoy D. Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India

Nema M. K. National Institute of Hydrology, Roorkee, India

Pandey Ashish Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Parhi Prabeer Kumar Centre for Water Engineering and Management, Central University of Jharkhand, Ranchi, India

Patle G. T. College of Agricultural Engineering and Post-Harvest Technology, Central Agricultural University, Gangtok, Sikkim, India

Pingale Santosh Murlidhar National Institute of Hydrology, Roorkee, India

Raj Abhay Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Raj Kumar M. Rajendra Mishra School of Engineering Entrepreneurship, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India

Rao M. Someshwar National Institute of Hydrology, Roorkee, Uttarakhand, India

Rathi Shweta Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India

Rawat Akash Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh, India

Sankhua R. N. Chief Engineer (South), NWDA, Ministry of Jal Shakti (WR,RD&GR), Hyderabad, India

Sherpa Tshering College of Agricultural Engineering and Post-Harvest Technology, Central Agricultural University, Gangtok, Sikkim, India

Shukla Chitra Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India

Singh Adarsh Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh, India

Singh Dhananjay Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, Uttarakhand, India

Singh Gagandeep Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Singh Pooja Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Singh Rajendra Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India

Singh Vijay P. Department of Biological and Agricultural Engineering and Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX, USA

Su Qiong Water Management & Hydrological Science, Texas A&M University, College Station, TX, USA;
Department of Agricultural Sciences, Clemson University, Clemson, SC, USA

Swain Sabyasachi Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Thakural L. N. National Institute of Hydrology, Roorkee, India

Tigabu Tibebe B. Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany

Tiwari K. N. Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India

Verdhen Anand Nalanda, Bihar, India

Wagner Paul D. Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany

Yadav Basant Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Yadav Brijesh Kumar Department of Hydrology, IIT-Roorkee, Roorkee, Uttarakhand, India

Yadav Vijay Kumar Indian Institute of Technology, Roorkee, India

Yamasaki Keigo Rural Promotion Division, Food and Agricultural Promotion Department, Nara Prefecture, Nara, Japan

Part I
Water Resources Management

Chapter 1
Water: How Secure Are We Under Climate Change?

Vijay P. Singh and Qiong Su

1.1 Introduction

Water is fundamental to sustainable social and economic development and the survival of ecosystems. It is required in most human activities, including municipal, agricultural, industrial, and energy uses, and is vital for the survival of all forms of life. Global water demand has increased dramatically over recent decades due to growing population, increasing industrialization and urbanization, growing demand for food and energy, rising living standards, and changing agricultural practices. At the same time, the availability of freshwater resources is threatened by climate change, including increased air temperature, changed precipitation patterns, reduced river flow, and more frequent and intensified hydrologic extremes. Currently, there are about 1.6–4 billion people estimated to be living in water-stress basins, depending on different metrics (Gosling and Arnell 2016; Mekonnen and Hoekstra 2016). Using the water stress index (WSI), defined as the ratio of annual mean total water withdrawal to available discharge, the world population under high water stress (WSI > 40%) is estimated to be about 2.3 billion (Stenzel et al. 2021). Such high water-stressed basins are mainly located in the Middle East, the Mediterranean, India, northern China, western United States, Mexico, the west coast of South America, and southern Asia (Fig. 1.1a). The population and regions suffering from high water stress tend to greatly increase in the future projection (Heinke et al. 2019; Stenzel et al. 2021; Wada et al. 2016). For example, a further 82% of the world population

V. P. Singh (✉)
Department of Biological and Agricultural Engineering and Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843-2117, USA
e-mail: vsingh@tamu.edu

Q. Su
Water Management & Hydrological Science, Texas A&M University, College Station, TX 77843, USA

Department of Agricultural Sciences, Clemson University, Clemson, SC 29634, USA

B. Yadav et al. (eds.), *Sustainability of Water Resources*, Water Science and Technology Library 116, https://doi.org/10.1007/978-3-031-13467-8_1

will be exposed to the high-water stress condition with climate change impacts alone, and the regions with high water stress will expand, as shown in Fig. 1.1b. Therefore, sustainable management of freshwater resources requires a better understanding of the likely impacts of climate change on global water security and how secure we are under climate change.

The objective of this paper is to highlight water security under the impacts of climate change. The paper is organized as follows. In Sect. 1.2, water security is defined, and its associated aspects are discussed. Section 1.3 presents the availability of water, water supply, water demand, and water consumption, followed by a discussion of the global water situation in Sect. 1.4. Section 1.5 discusses the causes of water scarcity, and Sect. 1.6 discusses how we can ameliorate water scarcity. The key issues and challenges that need urgent attention and their implications for water management are discussed in Sect. 1.7. The paper is concluded in Sect. 1.8.

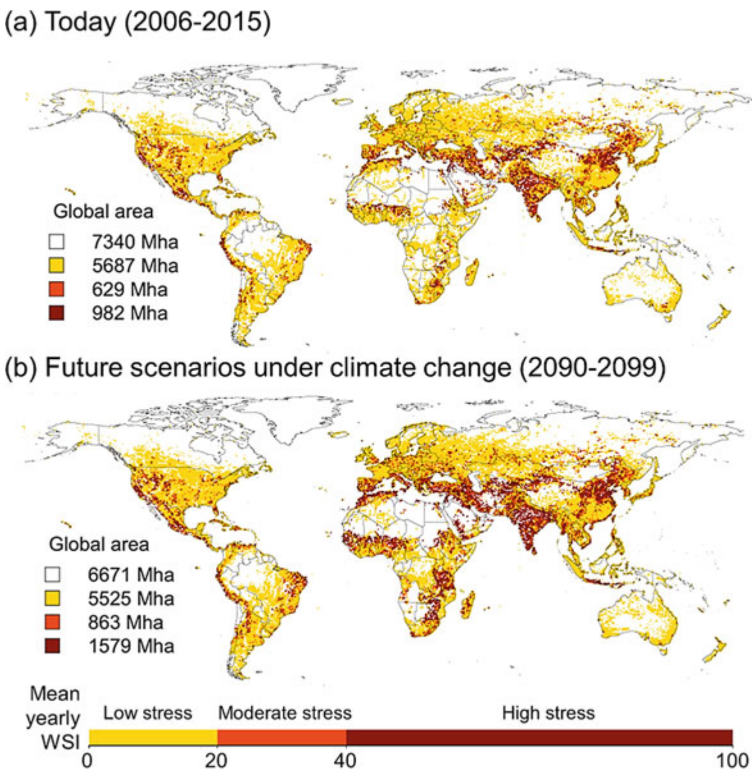

Fig. 1.1 Global distribution of water stress index (WSI) for (**a**) today (2006–2015) and (**b**) future scenario under climate change (2090–2099). WSI: 0–0.1% (no stress); 0.1–20% (low stress); 20–40% (moderate stress); and 40–100% (high stress). Adapted from Stenzel et al. (2021)

1.2 Water Security

The concept of water security was first introduced at the World Water Forum in 2000 (World Water Council 2000). Numerous definitions of water security have been proposed since then, and these definitions were described and compared in Cook and Bakker (2012), Allan et al. (2018), and Gerlak et al. (2018). Here, we define water security as access at all times to sufficient and quality water to satisfy varied needs, which is built on three pillars: (1) demand for and use of water, including appropriate use based on the knowledge of quality water and treatment; (2) availability or supply of water, ensuring sufficient quantities of water available on a consistent basis; and (3) access to water, having sufficient resources to obtain appropriate quantities of water for satisfying needs, as shown in Fig. 1.2.

In addition, there are several aspects of water security that need to be highlighted. All these three pillars of water security are heterogeneous across space and time. For the space dimension, water security should be managed and assured at (1) individual family unit; (2) village, town, district, state, and province; and (3) country, continent, and globe. Water stress across various basins within the same countries could significantly differ. For example, despite the low water stress at the country level in Australia, the United States, and South America, water stress in some basins in these countries or regions can be very severe (Fig. 1.1). Furthermore, the physical availability of water at large scales does not necessarily guarantee the accessibility of acceptable and safe use of water at local scales. For example, the low water stress

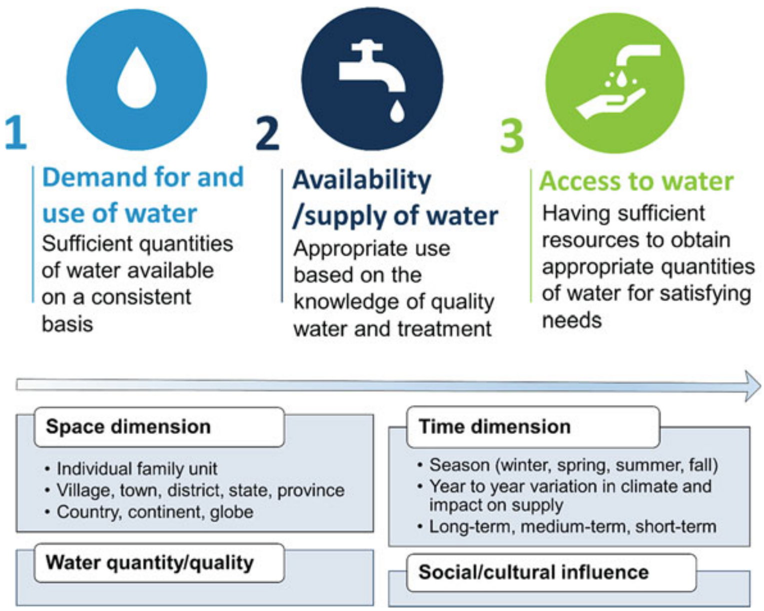

Fig. 1.2 Three pillars of water security, space and time dimensions, and other important aspects

in some African countries, as shown in Fig. 1.1, may mask the water scarcity at the household and individual levels due to insufficient water infrastructure to collect, transport, and treat water.

The time variability involved in water security includes (1) seasonal differences in water supply and demand; (2) annual variations in climate and their impacts on water supply; and (3) long-term, medium-term, and short-term plans for water security. For seasonal differences, the same regions may be affected by floods in the summer and drought in other seasons. Additionally, to satisfy water demand or needs, adequate quantity and proper quantity should be maintained simultaneously, which can affect the space and time dimensions of water security. The social and cultural influences on water security are continually evolving, making it exceedingly challenging to assure water security on an operational level.

1.3 Water Supply and Demand

1.3.1 Water Availability

Over 70% of the Earth surface is covered with water. However, 96.5% of the water is seawater, and about 0.9% is other saline water, which cannot be directly used by human beings (Fig. 1.3a). Only 2.5% of the water on Earth is freshwater, of which 68.7% is in the form of glaciers and permanent ice caps (Fig. 1.3b). Groundwater accounts for about 30.1% of the freshwater, and its global distribution is shown in Fig. 1.3c. Only about 1.2% of the freshwater is easily accessible to human beings in the form of wetlands, large lakes, reservoirs, and rivers (Fig. 1.3d). Freshwater is unevenly distributed in different countries (Fig. 1.4). Countries are generally considered water-stressed if their annual mean per capita freshwater availability, calculated in terms of long-term average runoff, is lower than 1700 m^3 per year.

1.3.2 Water Demand and Use

Generally, there are three major water uses, i.e., agriculture, domestic, and industry. Water use can be differentiated by water withdrawal and water consumption. Understanding the differences between water withdrawal and water consumption is important to properly evaluate water stress. Water withdrawal is defined as the total water removed from a water source, and part of this water can be returned to the water source, which reflects the competition among different water users. Water consumption, however, is the permanent lost of the total water from a water source, which is not available for other users locally. Water consumption is used to evaluate the impact of water use on water shortage.

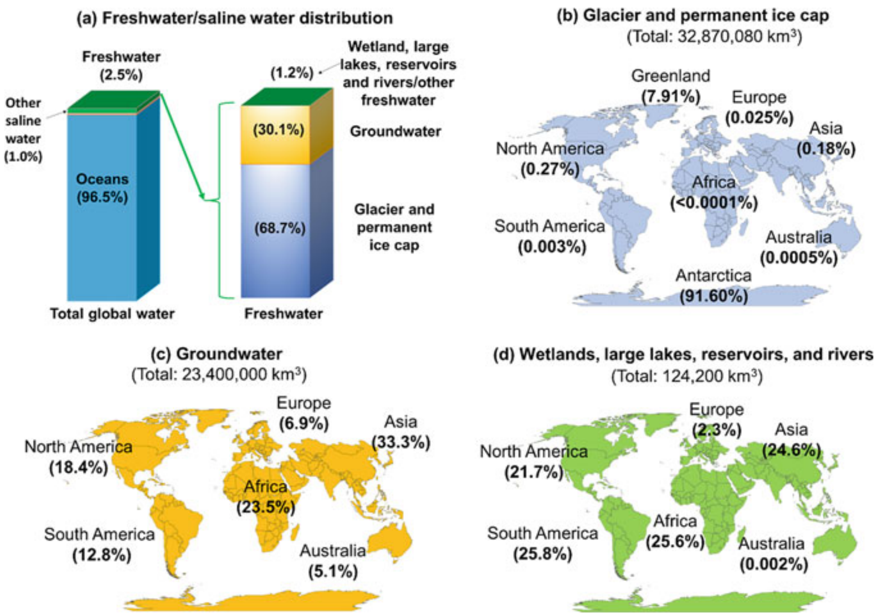

Fig. 1.3 World water resources distribution. Data from Igor (1999)

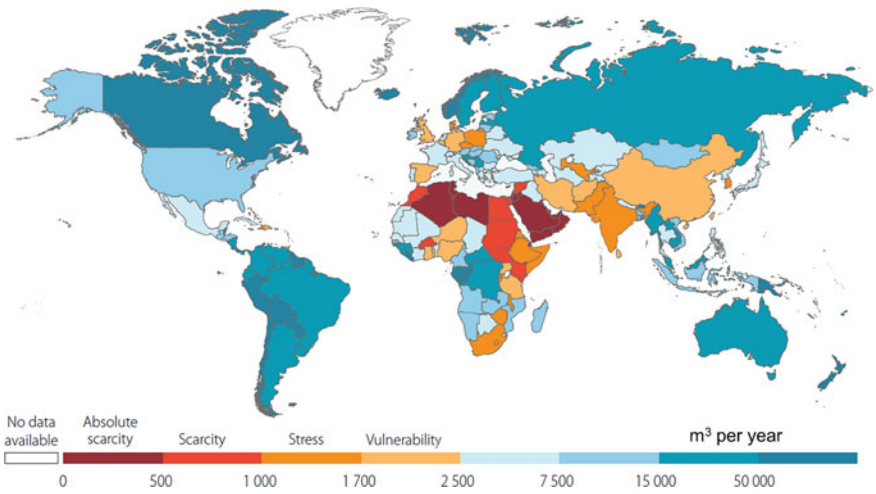

Fig. 1.4 Country-level per capita freshwater availability

Figure 1.5 shows the global water use in terms of water withdrawal and consumption by sectors. Agricultural sector, including irrigation, livestock, and aquaculture, is the largest water consumer, accounting for 69% of annual water withdrawal (Fig. 1.5a). Industrial sector, including primary energy production and power generation, accounts for 19% of annual water withdrawal, followed by the domestic sector, which accounts for 12%. For water consumption, irrigation alone accounts for 81% of annual water consumption (Fig. 1.5b, c). The top 7 largest water use countries consume about 48% of global water, i.e., India (13%), China (12%), the United States (9%), Russia (4%), Indonesia (4%), Nigeria (3%), and Brazil (3%).

Worldwide water withdrawal by sector varies with regions (Table 1.1). Agriculture consumes the largest share of freshwater in Africa, Asia, Latin America, and Oceania, but in North America and Europe, industry is the major consumer due to the industrial-dominated economy and more efficient irrigation system. In

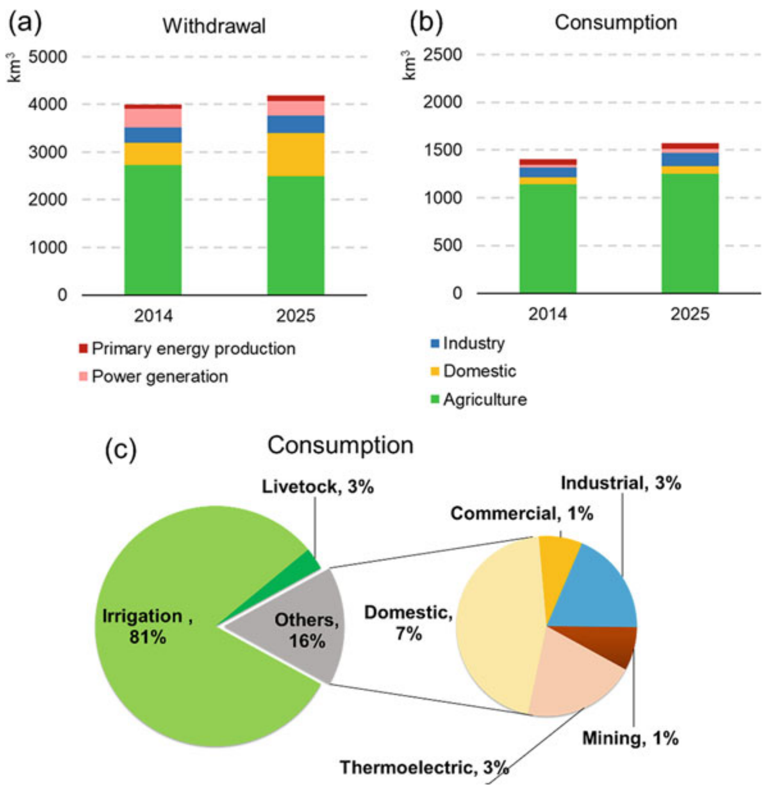

Fig. 1.5 Global water withdrawal and water consumption by sectors. Primary energy production includes fossil fuels and biofuel. Crops grown for biofuels is included in the primary energy production. Data from IEA (2016) and FAO, AQUASTAT (2016)

Table 1.1 The percentages of water withdrawal by sectors in different continents (%)

	Agriculture	Industry	Domestic
Asia	81	10	9
Africa	82	5	13
North America	37	50	13
Latin America & Caribbean	72	11	17
Europe	21	57	22
Oceanía	60	15	25

Data from FAO (2021)

contrast, Africa, Asia, and Latin America are agricultural economies, and the irrigation systems are not always efficient. The global share of the industrial sector is likely to increase in the future due to the booming economy in countries like China, India, and Brazil.

1.3.2.1 Domestic Water Use

Adequate quantity and quality of water for domestic uses should be first considered among different water uses. Although numerous studies have indicated that an adequate amount of water is vital for human health and well-being (Howard et al. 2020; Miller et al. 2021), insufficient evidence is available to define the adequate quantity and quality of daily water required for a person to lead to a healthy life. A recommended daily water requirement for drinking, cooking, food hygiene, and basic hygiene practices, such as handwashing and face washing, is 4–5 gallons (15–19 L) per day. However, a larger water amount is usually required to support improved hygiene. Assessment of recent water use from various European countries indicates that 19–21 gallons per day (70–80 L) is adequate for the pursuit of healthy and productive life (Biswas and Tortajada 2021). Per capita water use is highly associated with water accessibility, income level, and lifestyles. For example, the average American individual uses about 100–176 gallons (379–666 L) at home per day, while the average African family uses 5 gallons (19 L) per day due to the unreliable water supply and low-income levels to afford basic access to water.

The trends of daily per capita water use vary across different countries. Most countries have observed a declining trend in per capita water use recently, including the United States, all European counties, Singapore, Japan, and Australia (Biswas and Tortajada 2021). At the same time, per capita water use in other countries is increasing rapidly. For example, Middle Eastern and Northern African (MENA) countries are in absolute water scarcity situations with less than 500 m^3 of renewable freshwater resources per capita per year. Of these countries, Kuwait has the least per capita water availability, which was only 27 m^3 in 1970, and 9 m^3 in 2001, and is projected to decrease to 5 m^3 in 2025. However, per capita water consumption in Kuwait has increased dramatically from 200 L per person per day in the 1980s to 500 L per person per day now, which is among the highest in the world (Alazmi et al. 2022).

1.3.2.2 Water Use for Food Production

To satisfy the growing food demand, a large amount of water is needed to produce products and services. The concept of virtual water was first proposed by Allan (1993), which means the amount of water embedded in food products. There is a considerable variation in the virtual water required to produce different food and beverages (Table 1.2). For example, nearly 1222 L of water are required to produce one kilogram of maize. More water is needed to produce animal products, e.g., producing one kilogram of beef requires 15,415 L of water. Therefore, diet patterns significantly affect the water required to produce the food that a person needs every day. For example, for meaty American and European diets, the water requirement for food production can be as high as 5000 L per day, while for vegetarian African and Asia diets, only 2000 L per day are required. With rising living standards in the past several decades, there has been a steady increase in the demand for meat products in rapidly developing countries. For example, in China, the per capita meat consumption was only 20 kg per year in 1995, but it increased to 70 kg in 2015 (Min et al. 2015). The rise in meat consumption has resulted in high water demand for food production in China. Moreover, the shift in dietary habits is almost impossible to reverse. It is projected that an additional 407–515 $km^3\ y^{-1}$ of water, more than the total water use in Europe, is required in 2030 compared to the 2003 level due to the increasing consumption of meat products in China (Liu and Savenije 2008).

The amount of water used to grow crops varies significantly in different countries (Fig. 1.6), depending on many factors, including crop types, climate, soil types, and irrigation technologies used. There is a high potential to reduce the quantities of water required to produce agricultural products through more efficient irrigation techniques and better water management practices. For example, China has made significant improvements in increasing agricultural water use efficiency since 2010. From 1990 to 2012, water use per hectare of irrigation decreased by 22% due to the development of irrigation technology and institutional modification. The Chinese government plans to further increase water use efficiency in agricultural production in the coming decades. China's example has significant implications for reducing the global water requirements in agricultural production in the future. As shown in Fig. 1.6, agricultural water use efficiency in major water consumers like India and Brazil is relatively lower than that in the United States and China. Therefore, the water use for food production is likely to decrease significantly in these major countries in the future with more efficient irrigation management.

Table 1.2 Global average water requirement of different food and beverages (unit: L kg^{-1})

Food/beverages	Water requirement	Food/beverages	Water requirement
Chocolate	17,196	Coffee	1056
Beef	15,415	Peaches	910
Pork	5988	Apples	822
Chicken	4325	Wine	822
Rice	3400	Banana	790
Egg	3267	Oranges	560
Cheese	3178	Cucumber	353
Butter	3178	Beer	296
Olives	3015	Potatoes	287
Groundnuts	2782	Lettuce	237
Mango	1800	Cabbage	237
Wheat bread	1608	Tomatoes	214
Corn	1222	Tea	108

Data from Water Footprint Network (2022)

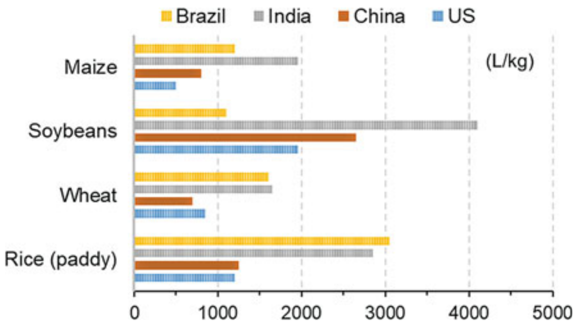

Fig. 1.6 Average amount of water needed to grow crops in different countries

1.3.2.3 Water Use for Energy Production

The production of energy resources, including fuel production and electricity generation, requires a significant amount of water. It is estimated that 471 km^3 of water withdrawal and 91 km^3 of water consumption are required annually for global energy production (IEA 2016). Electricity generation alone accounted for about 10% of global water withdrawal and 4% of water consumption (IEA 2016). For countries with high energy consumption, like the United States, the proportion of water withdrawn for thermoelectric production can be as high as 41% (Dieter et al. 2018). Freshwater is required for nearly all processes of electricity production, including fuel supply (extraction, processing, and transport), operation (cooling purpose), and plant infrastructure (material inputs of power plants) (Jin et al. 2019). Hence, water use efficiency of electricity production is highly dependent on fuel types (e.g., oil, nuclear, biomass, coal, and natural gas), cooling technologies (e.g., dry cooling), and power plant types. A global meta-analysis of water consumption of different electricity technologies by Jin et al. (2019) shows that large variations in water consumption were observed across different energy types (Fig. 1.7). Biofuel plants are the least water-efficient, with water use as high as 85,100 L MWh^{-1} (median of 23 plants), which is three orders of magnitude larger than other types of plants. Wind and photovoltaic plants use the least amount of water. Generally, hydropower plants are also water-efficient, but the water consumption of hydropower could be very high if the evaporative reservoir losses are included (Fig. 1.7). Accordingly, the mix of technologies deployed for electricity production can significantly affect regional and global water use. For example, for a 60-W incandescent light bulb burning for 12 h a day over one year in 111 million households (total number of U.S. homes), a fossil fuel thermoelectric power plant would consume about 3.0 km^3 of water. In contrast, most of this water could be saved if all were replaced by wind plants.

Energy generation contributes significantly to greenhouse gas emissions, and, therefore, accelerating the decarbonization of the energy system is important to meet global carbon mitigation goals. In this regard, negative emission technologies, such as bioenergy (liquid biofuels and solid biomass) with carbon capture and storage (BECCS), have gained increasing attention in recent years. However, bioenergy and carbon capture and storage (CCS) technologies are high water-intensive. For example, the energy consumption by biofuels (biodiesel and ethanol) only contributed to a small portion of the global energy consumption (0.25–1.4%, from 2008 to 2020), but it consumed nearly 20% of global water consumption of energy production in 2008 (Fig. 1.8). In addition, the use of CCS to capture and store carbon from thermal power plants can significantly increase water use. For example, the water consumption by plants equipped with CCS technologies increases by 29–81%,

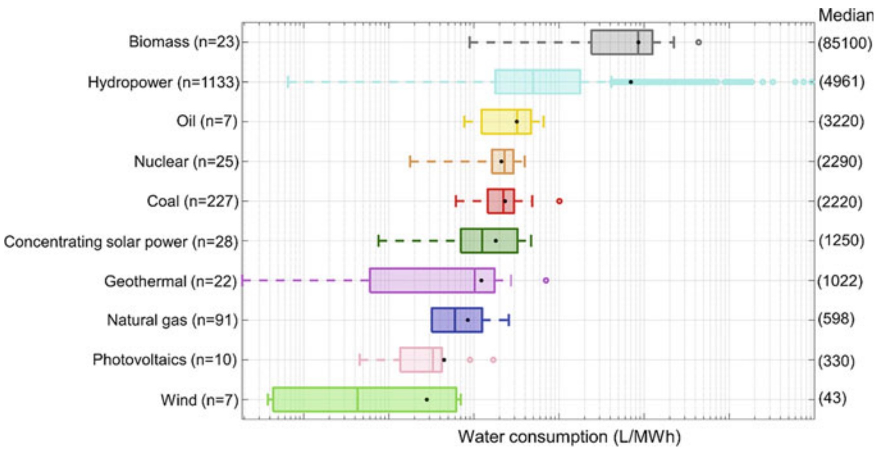

Fig. 1.7 Water consumption over the life cycle of different energy generation types. Water consumption is on a log scale. The term *n* represents the number of field data and the black dots represent the average values. Adapted from Jin et al. (2019)

depending on the fuel types and cooling types (Ali 2018; Chandel et al. 2011; Sharma and Mahapatra 2018; Talati et al. 2016). Currently, global land use for biofuel production is about 30 Mha, of which 30% is equipped with irrigation. A recent study by Stenzel et al. (2021) evaluated the impact of deploying BECCS on global water stress, which shows that the global population living under high water stress will increase from 2.3 billion (2005–2015) to 4.6 billion by the end of the twenty-first century, exceeding the impact of climate change. Therefore, the side effects of biofuels on global water stress require careful consideration.

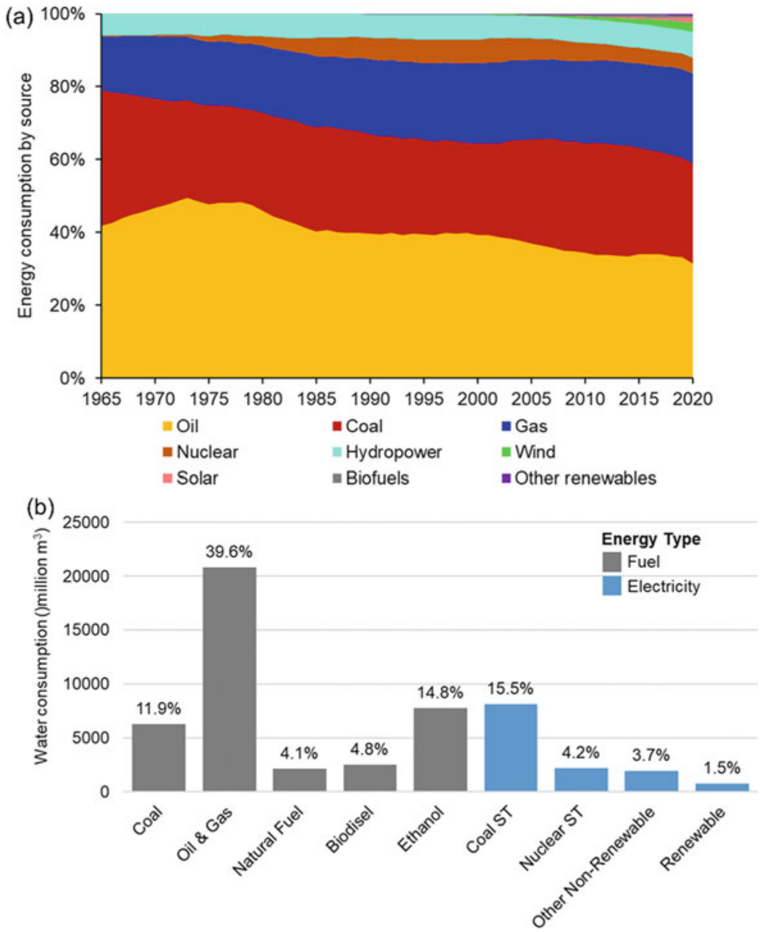

Fig. 1.8 **a** Global energy consumption by sources (1965–2020) and **b** water consumption for energy production by major energy category in 2008. Data in (**a**) are from https://ourworldindata.org/grapher/energy-consumption-by-source-and-region, and data in (**b**) is adapted from Spang et al. (2014)

1.4 Global Water Situation

Local water shortages are multiplying. Current patterns of use and abuse of water are not sustainable, and the amount being withdrawn is dangerously close to the limit and even beyond. Human interference with water bodies, such as dam and reservoir construction, regulation of rivers for navigation and transport, and diversion of water for irrigation, domestic and industrial use, has dramatically altered the connectivity and capacity of rivers, leading to ecosystem health degradation and biodiversity decline. Only 37% of the global longest rivers (longer than 1000 km) remain free-flowing, and they are restricted to remote regions, such as the Amazon basin, northern parts of North America, and the Congo basin in Africa (Grill et al. 2019). In addition, the source-to-sea connections are severely interrupted in about 54–77% of long rivers (>500 km). An alarming number of rivers fail to reach the sea, including the Indus in Pakistan, the Colorado River in the southwestern United States, the Rio Grande River on the Texas-Mexico border, the Murray-Daring in Australia, the Yellow River in China, and the Amu Darya and the Syr Darya in Central Asia. For example, the Colorado River, which originates in the Rocky Mountains, is the primary surface water resource in the southwestern United States, but the streamflow in the Upper Colorado River basin declined by 16.5% from 1916 to 2014 due to the reduced snowpacks and enhanced evapotranspiration under climate change (Xiao et al. 2018). At the same time, the Colorado River is heavily regulated by more than 100 dams and has not reached the sea since 1998 due to the overuse of water.

The altered flow characteristics of rivers have severe impacts on nutrient-rich sediment transport, riverside vegetation, aquatic species, and water quality. Excess pumping of water from rivers feeding the Aral Sea in Central Asia led to its collapse in 1980. The declining volume of freshwater in rivers also leads to seawater invasion in deltas, which considerably changes the balance between freshwater and seawater. Meanwhile, large-scale degradation and losses of freshwater habitats, including rivers, ponds, lakes, and wetlands, are continuing. For example, 64–71% of the world's wetlands have been drained, damaged, or destroyed since 1900, with a more significant loss rate in inland wetlands than in coastal ones (Davidson 2014). The ecosystem decay accelerates global biodiversity loss. Major land-based habitats have lost 20% of their native species since 1900. More than 9% of domesticated breeds of animals used for food had been extinct by 2016. This loss of diversity poses a significant risk to global food security.

Soil health is also changing. Soil erosion, nutrient imbalance, and soil organic carbon loss have become major global issues. Soil erosion from cropland is estimated to be 25–40 billion tons per year (FAO 2018). Together with soil erosion, a large amount of nitrogen and phosphorus pollutants are discharged into rivers, lakes, and estuaries, leading to the degradation of freshwater ecosystems (FAO 2018). The growing industrial point source discharge from developing countries also contributes to pollutant load. Nearly 1000 km^3 of wastewater is generated every year, but 92% of these waste streams in low-income countries are discharged without being treated into the receiving stream waters (Lu et al. 2018). Over the past three decades, water pollution has become a severe issue in many countries in Asia, Africa, and Latin America (United Nations 2015).

Groundwater is the major source for irrigation and domestic use when surface water is limited. Globally, about 800 km^3 of groundwater was abstracted and consumed annually in the 2010s, which provides nearly 50% of global water used for irrigation and drinking for billions of people. India, the United States, China, Pakistan, Iran, Mexico, and Saudi Arabia are the top seven groundwater consumers, which account for 75% of the total global groundwater pumping. It is reported that 3.6 billion people in 18 countries are overpumping their aquifers, and 5–20% of global wells are at risk of running dry if groundwater levels decline by even a few meters (Jasechko and Perrone 2021). Groundwater withdrawal, combined with surface water diversion and land-use change, can explain 33% of the observed sea-level rise in the twentieth century (Sahagian et al. 1994). More than 15% of the coastal aquifers in the United States are threatened by seawater intrusion, leading to increased groundwater salinity (Jasechko et al. 2020).

Large-scale intensive droughts have been observed in Australia (Tian et al. 2020; van Dijk et al. 2013), Brazil (Cunha et al. 2019), China (Yao et al. 2018), the United States (Rippey 2015), India (Mishra et al. 2019), and Russia (Cook et al. 2020) from 1960 to 2018. These severe droughts occur more frequently (He et al. 2020), which can significantly affect crop production and disrupt food stability (Kuwayama et al. 2019). In 2017, 22.4% of the world population was under high agriculture production/yields vulnerability to severe drought (FAO 2018). In countries and regions which are highly dependent on hydroelectric power, e.g., Brazil and South America, repeated brownouts were expected due to not having enough water to drive turbines (Cuartas et al. 2022). Water security is closely linked to the security of energy, food ecosystems, and soil health. There seems to be a global water crisis that is impacting supplies of food and the generation of energy and other goods.

1.5 Causes of Water Scarcity

The causes of water scarcity can be attributable to the population rise, higher food and energy requirements leading to higher water requirements, economic development, changing consumption patterns changes due to rising standard of living, and climate change.

1.5.1 Demography

Since the 1950s, global population has witnessed a rapid rise (Fig. 1.9a). Over the past 70 years (1950–2019), the population has increased from 2.6 billion to 7.7 billion, and water withdrawal has increased by nearly 500%. As shown in Fig. 1.9b, the demand for water increases much faster than the population and economic development.

Population is likely to rise by another 1.7–2.5 billion (22–34%) by 2050 compared with 2019. The demand for water would rise by 20–30% by 2050 under an optimistic estimation (FAO 2018), roughly 900–1400 km^3 per year. In addition, not just the absolute number, the shift in dietary habits to animal-based products can make a big difference. Global food demand is projected to increase by 14–65% from 2020 to 2050, based on the estimations from different studies (Fukase and Martin 2020; van Dijk et al. 2021). If there is no change in agricultural efficiency, the world will need 14–65% more water withdrawal for agriculture to feed the extra 1.7–2.5 billion mouths. The additional water requirement is about 451–2093 km^3 of water, equivalent to 28–46% of current global water use.

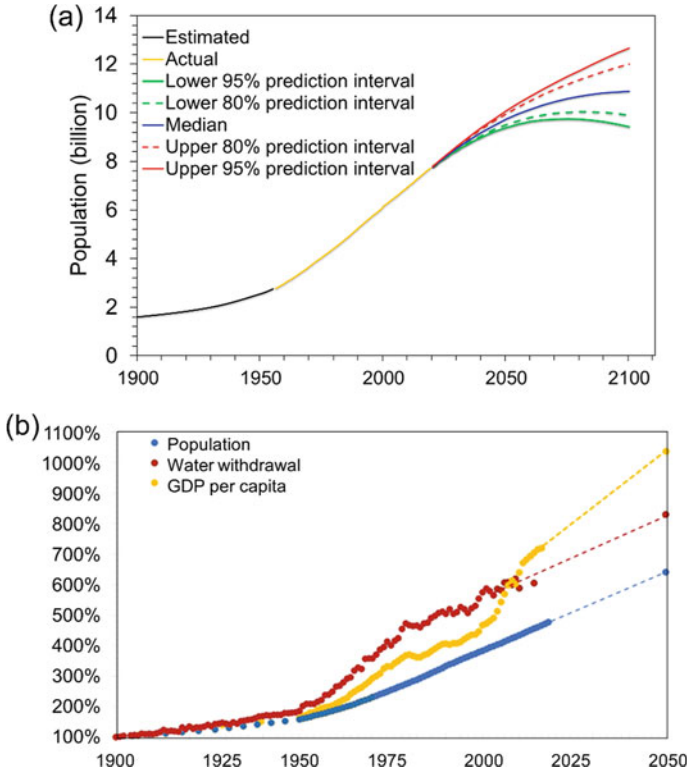

Fig. 1.9 **a** Global population growth. Data from United Nations, DESA, Population Division, World Population Prospects 2019. http://population.un.org/wpp/; and **b** relative change of population, water withdrawal, Gross domestic product (GDP) per capita compared to 1990. Adapted from Boretti and Rosa (2019)

1.5.2 Climate Change

Climate is a long-term average of weather (such as temperature, precipitation, or winds), defined as the statistical mean conditions over certain years, typically three decades. Climate change refers to changes in climate that are in excess of natural variability and attributable to human activities. Since the pre-industrial period (1980–1990), the mean land surface air temperature increased by 1.53 °C, and this warming is not evenly distributed across the world (IPCC 2019). Climate change impacts include rising air temperature, changing hydrologic cycle, increased frequency and intensity of extreme weather events, melting of glaciers and snow, permafrost degradation, increased soil erosion, coastal degradation, sea-level rise, water quality degradation, and increased wildfire occurrence (Hurlbert et al. 2019). Climate change leads to increased risks to water availability (Elliott et al. 2014; Haddeland et al. 2014; Hagemann et al. 2013), reduced crop yield (Iizumi and Ramankutty 2016; Iizumi et al. 2018; Piao et al. 2010), higher energy demand (van Ruijven et al. 2019), loss of biodiversity (Araujo and Rahbek 2006; Bellard et al. 2012; Fitzmaurice 2021), and increased human health risks (Patz and Olson 2006).

Climate change has implications for food security, water resources, energy production, ecosystem health, extreme hazards, human society, ecosphere, and biosphere. The IPCC sixth assessment report states that global surface temperature will continue to rise, and the global warming of 1.5–2 °C will be exceeded in the twenty-first century if no significant greenhouse gas emissions reduction occurs in the coming decades (IPCC 2021). Climate change can directly affect the way plants grow through increased air temperature and CO_2 fertilization (Iizumi and Ramankutty 2016; Iizumi et al. 2018; Piao et al. 2010) and therefore change the water use pattern of plants (Haddeland et al. 2014; Konapala et al. 2020). Climate change can also affect plant growth by changing water quantities and quality and accelerating land degradation. In addition, trees can be impacted during heavy rain; plants can dry up of biomass during drought; crops can grow rapidly and then wilt in a warming climate. Considerable crop production loss is projected in the future, even with immediate greenhouse gas emission reductions (IPCC 2019). Climate change-induced rising water temperatures, declining river flow, and enhanced precipitation intensity may exacerbate water pollution and affect ecosystem health, biodiversity, and human health.

Climate change tends to intensify the hydrological cycle, and the types of hydrological changes or impacts include (1) freshwater availability: decrease of global renewable surface water (Schewe et al. 2014) and groundwater (Portmann et al. 2013), particularly in most dry subtropical regions, but an increase is found at high latitudes; (2) freshwater storage: decrease of natural water storage due to reduced snow and ice water storage and increased evaporation from lakes, reservoirs, wetland, and shallow aquifers (IPCC 2021); (3) rainfall variability: higher frequency and intensity of heavy rainfall events in major agricultural production areas, e.g., south, east, and southeast Asia (IPCC 2021); (4) runoff variability: decreased annual mean runoff in most dry tropical regions and increased runoff in wet tropics and at high latitudes; (5) flow variability: reduced snowmelt discharge and maximum spring snow depth in regions