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Desalination and Water Security

Chris Anastasi

Desalination and Water Security

Desalination is to the water industry what renewables are to the electricity sector. However, unlike renewables, the former is being deployed in a quiet revolution away from public glare.

This book provides a holistic view of desalination, highlighting the important role this technology can play in providing safe access to water across the globe. It describes the context for this technology to flourish in the coming decades. It discusses the pressures on freshwater resources and the key role the desalination industry plays as it moves from a good-to-have provider today to a must-have mainstream water solution in the future. The book explores the vital elements of the desalination industry, including the winning technologies and how further technological developments will reduce costs and increase deployment into new areas. It also addresses the energy used and the key environmental issues of carbon dioxide emissions and brine waste production. Using a series of country case studies, the book illustrates how desalination can supplement natural water resources in different environments and for different purposes, and how it is supporting domestic and economic activity. Providing a forward-thinking assessment, the book considers developments over the next 30 years as climate change impacts become even more apparent.

This book will be of great interest to those working to alleviate water scarcity and improve water security. It will also be of interest to those in water resource management, water policy and regulation, water science, and environmental engineering.

Chris Anastasi is an industry professional, academic, consultant, and author. He is an expert on energy, climate change, and other environmental issues related to sustainable development and in scenario analysis. He has worked for major international companies and acted as an advisor to national and international institutions. He was previously a Senior Lecturer at the University of York in the UK and acted as a Visiting-Professor at the University of Maastricht in the Netherlands. He is the author of two books, *Strategic Stakeholder Engagement* (Routledge, 2018) and *Who Needs Nuclear Power* (Routledge, 2021).

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For those who have helped me on my way,
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Foreword

With global shifting weather patterns, rising temperatures, a growing population, and expanding global industrial developments, the demand for reliable, clean, and potable water has reached unprecedented levels.

Approximately 71% of the Earth's surface is covered by water, of which 97.4% is saltwater. Except for surface water and some groundwater, most of the freshwater is not readily accessible for human use. In dry areas, overextraction of the groundwater has often resulted in land subsidence.

The current climate crisis has thrust the issue of water scarcity to the forefront and has demanded innovative solutions to tackle such a pressing global challenge. Desalination technologies in general, and particularly membrane-based desalination technologies with their ability to convert abundant saltwater into freshwater, could provide a great opportunity for a more sustainable future.

In the last two decades, with advancements in technology and engineering, desalination has evolved from a niche concept to a viable and scalable method of producing pure water. It has been playing a vital role in dry regions such as the Middle East and North Africa region, have prolonged droughts and unreliable rainfall. In addition, desalination technology has provided increased resilience of water supply in coastal regions, which are often densely populated and prone to water stress. In the United States, California and Texas are prime examples of such applications. In those regions, desalinated water is also used for aquifer recharge.

Another application of the membrane-based desalination technology at smaller scales is during disastrous events where the availability of freshwater supply is critical. Containerised desalination plants have been utilised where access to seawater is readily available.

While desalination technology presents a promising solution, it is not without its challenges. Energy consumption, environmental impacts, and cost-effectiveness are among the key considerations that must be addressed to ensure the long-term viability and sustainability of desalination projects.

Overall, desalination technology has emerged as a game-changer in the pursuit of water security in our rapidly changing climate. This technology has great potential to improve water scarcity and promote sustainable development.

Dr Abraham Negaresh, Thames Gateway Desalination Plant, Thames Water Utilities, UK

It is easy to think when you live in the UK that you live in a water-abundant society. In fact, our popular culture is littered with 'the rain,' whether that be our recollections of wet Wimbledon tournaments or my own memories of wet summer holidays with my family. The reality is different, however, and climate change has had a significant impact on rainfall within London and South-East England. This region receives roughly the same amount of rainfall as Jerusalem every year, and with predictions that the temperature will continue to rise in the forthcoming years, suppliers, legislators, and the public need to consider their relationship with both the production and consumption of our most precious resource.

Thames Water opened the Thames Gateway (previously Beckton) desalination plant in 2010 with a design capacity of around 150 million litres of water a day (able to service the needs of about 400,000 households). It was the first of its kind in the UK and more commonly seen in countries with higher water stress than the UK. It was built because of two major drivers that were emerging at the time. Firstly, ongoing climate change would increase water stress, and secondly, the population of London would increase by around 700,000 people by 2021. Both assumptions have turned out to be true, with the actual population of the London area increasing by about a million people over the same period.

The plant does not exist to provide a daily water supply as the economics of producing water via the Reverse Osmosis technology versus normal water production do not really make sense – particularly in a high energy cost environment - but it is designed to provide an important role as a short-to-medium-term solution in periods of high-water stress and exists largely in that contingency capacity.

As we think about water resilience in the southeast of England over the coming years, we have an impetus across the water sector to reduce waste of water both within the supply networks but also within consumers' homes. Several schemes to address water shortages are currently being proposed across the southeast, although none will replicate the desalination plant in place now. Whilst there are new sites being proposed in the southwest of England, these will take several years to come online, so for the UK mainland at least, the Thames Gateway desalination plant remains one of its kind.

This book is timely, providing a holistic view of the industry at an important time in its development. It discusses the changing context for the desalination industry as the impacts of climate change become even more apparent and introduces the technologies involved and their implications for energy and the environment. The book also illustrates the use of desalination across the world through a series of country case studies. It also explores its potential role in the middle of this century to better understand whether the industry can provide the level of water security needed in a challenging global environment.

David Wylie, Director of Commercial and Procurement,
Thames Water Utilities, UK

Preface

To quote my great-grandfather, *life is sweet*. This is made possible by the ready availability of freshwater, which is critical to the well-being of people and the environment they inhabit. Rising populations, economic development, and the depletion of natural reservoirs have made water a major issue in many regions of the world. Changing weather patterns, brought about by man-made perturbations to the natural environment, will make matters worse. Government and industry around the world will have to address water shortages in their countries, in some cases severe and for extended periods.

On the book content

Climate change is a key issue for the world today. The introduction to this book in Chapter 1 discusses the drivers for this phenomenon, the emission of carbon dioxide and other greenhouse gases, and the associated rise in global temperatures. The response by decision-makers has been less than is needed, and the indications are that the world will fail to meet targets agreed for 2050. There are major implications for renewable freshwater resources and water scarcity; the extent of the problem and potential solutions are explored in Chapter 2.

Technology, in the form of desalination, can help alleviate the problem. In many ways, this technology is to the water industry what renewables are to the electricity sector, the difference being that desalination is being deployed in a quiet revolution away from the public glare. The aim of this book is to take a holistic view of the desalination industry, highlighting its benefits and its limitations. It will describe the changing context for the technology in the coming decades as it moves from a 'good-to-have' contributor to the freshwater provision to a 'must-have', mainstream water solution, particularly for the domestic sector. The conditions for this transformation will be discussed, and the potential scale of its contribution to water supply and the associated implications for energy, and the environment will be assessed over the period to 2050.

As indicated above, the key drivers for increasing pressure on freshwater supplies in many parts of the world are discussed in Chapter 2 with a particular focus on the role of population growth, economic development, and climate change. The latter increases the pressure on supplies in some regions today and will do so increasingly over the next thirty years, and the interplay between climate change, energy and the provision of freshwater supplies will be explored.

The status of the industry is established in Chapter 3, including the number and regional distribution of the plants commissioned, the types of technologies deployed, and the production capacity. Key aspects of the desalination industry, including the quality of water delivered, the economics of production and the price of water, and the 'winning' technologies, are discussed. Technological development and 'learning', both of which reduce costs and make deployment into new jurisdictions easier, are also explored. Energy and the environment are important considerations for the industry, and the way in which both of these issues determine the nature of the technologies adopted and the scale of deployment is discussed in Chapter 4. The role of the key stakeholders in encouraging or opposing the deployment of this critical water infrastructure is also an important consideration.

A series of country case studies are presented in Chapter 5 that serve to illustrate the remarkable geographical reach of the industry. They also cover key aspects of each country, including the renewable freshwater and groundwater resources, the desalination technology adopted, the nature of the feedwater for the process, how the water produced is used, and the availability or otherwise of indigenous energy supplies. The increasingly important role of desalination in supplementing natural water resources in different regions is highlighted, and the country case studies presented illustrate how desalination is playing an important role in water provision for domestic consumption and economic activity.

It is important to assess how the industry will evolve in the crucial period to 2050. Looking ahead, then, converging developments that could lead to rapid growth in the deployment of this technology are highlighted. They include trends in society, the political arena, economic activity, technical progress, and their interaction. Such converging developments are captured in several scenario analyses carried out by internationally renowned institutions, and it is possible to draw on them to create simple analytical descriptions of the future. Potential scenarios for the deployment of desalination technology in the period to the middle of this century are developed in Chapter 6 and provide some insights into the overall production capacity, the number of plants needed to deliver it, and the implications for energy consumption and the environment.

Having taken a holistic view of desalination, Chapter 7 provides some reflections on the importance of this technology as a source of pure water alongside the other options. It highlights the key role that desalination will play in the future, particularly in the provision of drinking water in some countries. It is a global industry, set to grow significantly over the next two or three decades, and as such, there will continue to be new entrants into the supply chain, bringing new innovations and approaches.

On the information and data used in the book

The water and energy industries are intimately linked with one another. There are, however, important differences in the quality of the data and information available. The energy industry has been international in nature almost from its beginning in the early twentieth century, with governments taking a keen interest in the sector and major companies emerging to service the needs of markets around the world. The climate change issue has also shone a spotlight on energy and the need for accurate data at the national, regional, and global level, and this has been forthcoming.

The water industry, on the other hand, is made up of national markets, and, except for rivers, there is little transport of this resource across national borders. The lack of an international market for water removes an important driver for comprehensive, harmonised, and reliable data sets over an extended period. The water scarcity issue, with climate change an important contributor, is driving interest in data and information about national water resources, including desalination.

The analyses presented in this book draw on the data published by institutions such as the World Bank and the United Nations and some excellent published papers in learned journals. The sources do not necessarily cover the same periods or focus on the same issues, and it is sometimes difficult to reconcile the data and information presented across publications. Nonetheless, the key observations derived from the various data sets are broadly consistent and can provide a picture of the evolution of, for example, the available renewable freshwater resources, water scarcity, and the role of desalination in meeting the needs of a burgeoning global population.

Chris Anastasi, November 2023

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I would like to thank Hannah Ferguson and Katie Stokes at Routledge, who saw merit in the subject matter and helped steer me through its publication. I am very grateful for their advice, support, and patience, which made writing the book easier and enjoyable.

My interest in desalination started in the 1990s, when I was working on scenario development with the fabled Shell Group Planning Team. I helped developed Shell's first long-term energy scenarios, which covered the period 1860–2060 and it was clear then that water scarcity would be an increasingly challenging issue and that desalination was an important emerging technology. It is appropriate, then, that I thank Roger Rainbow for giving me the opportunity to work on such an interesting scenario project.

I was fortunate to visit two operational plants during my research: the Dhekelia Desalination Plant in Cyprus, and the Gateway (formerly Beckton) Desalination Plant in England. These were very helpful site visits, and I would like to thank Demetris Petrou for allowing me to visit the Dhekelia site and Vasiliki Daniel for showing me the plant and David Wylie and Abraham Nagaresh of Thames Water for hosting my visit to Gateway.

I would also like to thank Tony Marinaro and Charlie Morley, Tony for many interesting discussions on the topic of water over the last couple of years, and Charlie for turning my charts into excellent figures in the book.

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1 Introduction

Climate change is the defining issue for the 21st century with major implications for freshwater supplies in many regions across the world.

1.1 A challenging world

The world faces many challenges this century. The inexorable rise in population, the drive for economic development, the unsustainable consumption of the earth's resources, and perhaps the most challenging of all, the unravelling of climate change. These converging developments will make for a very uncomfortable world for billions of people. There is hope and expectation that innovation, new technologies, greater resource efficiency, and changing behaviour will help address these challenges as they have in the past. Major investment in new, improved infrastructure in energy, water, transport, and communications *could* facilitate the step-change needed in the period to 2050, but the evidence that this could occur is not promising.

Climate change is the defining issue of the 21st century. Signals indicating a potential change in our climate in the form of increasing atmospheric concentrations of greenhouse gases have been with us for decades. It has long been understood that carbon dioxide (CO_2) and water are greenhouse agents, that is, they are transparent to radiation from the sun and absorb the radiation emitted by the earth; they help maintain the temperature of the atmosphere, and the earth's surface in contact with it, at habitable levels. The physics is clear: increasing the concentration of these and other greenhouse agents increases the absorptive capacity of the atmosphere; this raises the global temperature and changes the climate.

There is, then, a question as to whether it is possible, even at this late stage, to lessen the impacts of this phenomenon and if not, how best to ensure basic needs such as the provision of freshwater for a growing global population are met.

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1.2 Carbon dioxide emissions

The scientific evidence for climate change and the impacts on the environment, both global and local, has become increasingly apparent. Human activity leads to increased emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and sulphur hexafluoride (SF_6) gases. Although there are some removal processes for CO_2 and CH_4, the concentrations of all these gases in the atmosphere have risen markedly in the past 50 years or so; their ability to trap the earth's radiation in a 'greenhouse effect' has led to an increase in global temperatures and changing climate patterns.

There are estimates of the cumulative emission of CO_2 into the atmosphere since the start of the industrial revolution and this shows that the United States is by far the largest contributor at around 420 billion tonnes over the period 1750–2020. The next two major contributors are the EU's 27 countries combined and China, emitting an estimated 290 and 230 billion tonnes, respectively. The United Kingdom, the country that led the industrial revolution, has emitted about 80 billion tonnes total during this period.

Carbon dioxide emissions over the period 1965–2020 and those in 2020 are also important metrics. The ten largest CO_2 emitters over the period 1965–2020, cumulatively, were the USA, China, Russia, Japan, Germany, India, the United Kingdom, Canada, France, and Italy. The world's ten largest CO_2 emitters in 2020 were China, the USA, India, Russia, Japan, Iran, Germany, South Korea, Saudi Arabia, and Indonesia; together, these countries emitted 69% of the world's total CO_2 emissions; many of the countries listed are present in both metrics. It is incumbent, then, on these countries to step up their greenhouse gas emission reduction efforts since they have gained most from the use of fossil fuels over the past 50 years.

To these countries must be added Brazil because of its pivotal role in deforestation over the past few decades, an activity that releases large quantities of CO_2 stored as biomass. This activity also paves the way for other economic activity, such as cattle farming, and this results in further greenhouse gas emissions. Although Brazil is the custodian of this valuable forest resource, it is important the developed and richer nations provide financial and other support to maintain it for the world.

1.3 Atmospheric concentrations of greenhouse gases

The concentration of CO_2 in the atmosphere in the pre-industrial period of the 18th century was just 280 parts per million (ppm) and had remained at about this level for the last million years or so. Since then, it has risen significantly, driven by the combustion of fossil fuels, first by coal, which underpinned the industrial revolution, and then by oil, which facilitated the emergence of mass transport systems on land, air, and sea; most recently, gas has been the preferred fuel for domestic heating and power generation. Deforestation in many

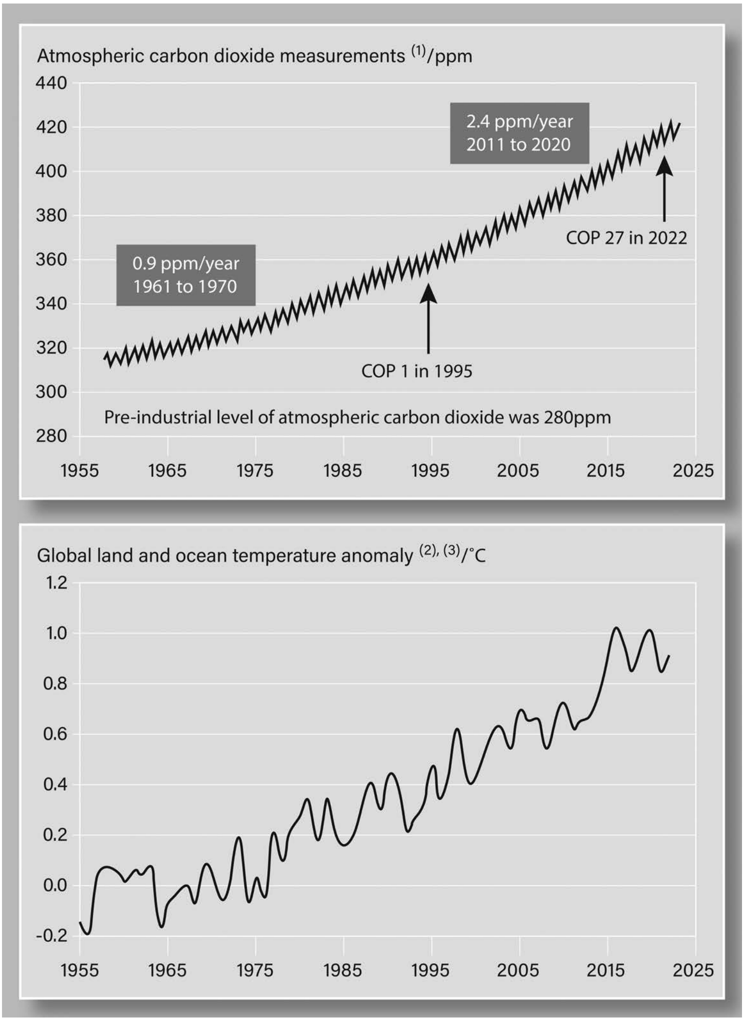

Figure 1.1 Rise in atmospheric carbon dioxide and global temperatures

Sources: (1), Data from the Global Monitoring Laboratory, Earth System Research Laboratories, NOAA; (2), Global land and ocean temperature anomalies 1880–2022, Erick Burgueño Salas, Statista, April 2023.

Note: (3), Temperature anomalies represent the difference from an average or baseline temperature, in this case the 20th century average. ppm, parts per million; COP, Conference of the Parties.

parts of the world also released large quantities of CO_2 into the atmosphere as countries sought economic development for their growing populations.

Some of the CO_2 emitted is absorbed by the earth's vegetation and the oceans. However, the estimated absorptive capacity of the earth's biosystem and oceans appears to have declined over the past century or so and most of the CO_2 emitted accumulates in the atmosphere and remains there for hundreds of years.

Accurate and direct measurements of atmospheric CO_2 are taken at the Mauna Loa Observatory in Hawaii, which began in earnest in 1958. The early measurements at this site confirmed that atmospheric CO_2 had risen to about 315 parts per million (ppm), an increase of just 35 ppm in the 150 years or so since the onset of the industrial revolution. However, the concentration measured rose significantly in the next 70 years, to about 420 ppm in 2022. To put this into context, a person born in 1950 would have seen an increase of over 30% in atmospheric CO_2, or 100 ppm, in their lifetime. As indicated above, this level of atmospheric CO_2 has not been seen for a million years and is set to continue to rise for much of this century, even with a strong decarbonisation response by the global community. Perhaps most worrying is the fact that two major recent perturbations to the world system – the 2008 financial crisis and the COVID pandemic – have had little effect on the inexorable rise in atmospheric CO_2.

The atmospheric concentrations of the other main contributing greenhouse gases – CH_4, N_2O, and SF_6 – are also rising. Sources of CH_4 include emissions from fossil fuel production and leakage during its transport, sometimes over very long distances; other major sources include the emission from the decay of organic matter in wetlands, including rice production, and from ruminant animals such as cows. The lifetime of CH_4 in the atmosphere is relatively short, at about 12 years. N_2O sources include agriculture, fuel combustion, wastewater management, and industrial processes; it has an estimated lifetime in the atmosphere of about 115 years. SF_6, a very stable chemical with a lifetime of 3,200 years, is used in electrical transmission and distribution equipment, the manufacture of electronics, and the production of aluminium and magnesium. Underpinning all these emissions is the economic development of a growing global population.

The recorded concentration of CH_4 has risen from 1,645 parts per billion (ppb) in 1984 to 1,912 ppb in 2022; that for N_2O has risen from 316 ppb in 2001 to 336 ppb in 2022; and that for SF_6 from just over 4 parts per trillion (ppt) in 1995 to about 11 ppt in 2022. Although these concentrations are much lower than those for CO_2, their Global Warming Potential (GWP) is much higher: CH_4 is about 20 times more potent than CO_2 as a greenhouse agent over a one-century timescale, while N_2O and SF_6 are about 300 and 24,000 times more effective than CO_2, respectively, over the same timescale. Reducing the emission of these gases is also an important activity in addressing climate change.

1.4 Global temperatures

The average global temperature has also been rising. When compared to the 20th-century average, the observed temperature has been consistently warmer in the period 1980–2022; this contrasts with observed temperatures in the period 1880–1935 which were consistently colder when compared to the same average. The size of these temperature 'anomalies' is also significant: they are now almost 1°C above the average in the most recent period, compared with a maximum of 0.5°C below the average in the earlier period. The warmest years on record have been recorded over the past decade, and this has once again prompted a call for action to limit average global temperatures to 1.5°C by 2050.

Climate change is a complex issue, and its manifestations are many. Some are small scale, regional in nature, and relatively short-lived such as extreme weather events; others are much larger scale, more dramatic, and longer lasting, such as droughts and aridification. There is also the possibility of what are irreversible events, at least on the human timescale, such as melting of the polar icecaps and weakening of the Atlantic Meridional Overturn Current (AMOC). The latter circulates water from north to south and back in a long cycle within the Atlantic Ocean, bringing warmth to various parts of the world; it also carries nutrients vital to ocean life.

Recent research shows that the AMOC has weakened by about 15% compared to historic norms, brought about by increased rainfall in the North Atlantic resulting from global warming (and evaporation) in the tropics; this has the effect of reducing ocean water density and altering the flow of the current. The North Atlantic is cooling, and many countries, in Northern Europe, for example, will experience much cooler temperatures while in other parts of the world, temperatures will be higher.

Most concerning is that if this process continues, there is an increasing likelihood that it will reach a tipping point where it may 'switch off' completely. The last time the AMOC 'shut down' was towards the end of the last ice age, about 14,500 years ago. Then glacial melt flooded the North Atlantic with freshwater, altering the salinity of ocean water and collapsing the system, causing temperatures in Europe to fall significantly.

1.5 Global response to climate change

No part of the earth is immune from the effects of climate change. Renewed efforts to reduce greenhouse gas emissions will help lessen the impacts of this phenomenon, but people will also have to learn to adapt to their new environment. This is not a new prospect, as evidenced by the many sites around the world that now lie abandoned and lost to history following changed environmental circumstances. People, then, have had to adapt to dramatic changes in their environment, perhaps through the adoption of new technology and practices or, in extreme cases, by migrating to regions less affected. But the scale of the problem and the implications for the populations involved are much greater than before, making some options more difficult than in the past.

The Paris Agreement was a seminal Conference of the Parties (COP) held in 2015 and is a legally binding international treaty on climate change. It was adopted by 196 Parties and entered into force in 2016. Its goal is to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. The Agreement works on a five-year cycle of increasingly ambitious climate action carried out by countries. The latter were required to submit their plans for action in the form of Nationally Determined Contributions (NDCs) by 2020. In their NDCs, countries outline actions they will take to reduce their greenhouse gas emissions to reach the goals of the Paris Agreement. Also, countries suggest the actions they will take to build resilience and to adapt to the impacts of rising temperatures.

The 2020s decade is a crucial one for action on climate change, requiring a step-change reduction in greenhouse gas emissions if the world is to avoid the effects of rising global temperatures. It was, then, important that the 26th Conference of the Parties (COP26) in Glasgow signal that countries are serious about meeting their 2030 obligations under the Paris Agreement. It was also important that there was recognition of the need to go further and sooner if average global temperatures are to be limited to no more than 2.0°C and preferably 1.5°C above pre-industrial levels, as agreed in Paris.

The COP26 agreement, the Glasgow Climate Pact, suggested some progress was made, particularly in four key areas: CH_4 emissions, the use of coal, deforestation, and financial support for poorer countries impacted by climate change. As indicated above, CH_4 is a particularly damaging greenhouse gas, and the Pact set a 30% reduction target in CH_4 emissions by 2030; this was signed by over 100 countries, although three major emitters – China, Russia, and India – did not. Coal featured in a COP agreement for the first time with a pledge to phase down (not phase out) its use, although no timescale was suggested and two key coal users – China and India – were reluctant to support stronger measures at this time due to their heavy reliance on this fuel.

Deforestation has been a major concern for decades. Well over 100 countries accounting for 85% of the world's forests, agreed to stop deforestation by 2030. Crucially, Brazil, the custodian of the vast Amazonian Forest, was one of signatories, and their action on this issue will be closely scrutinised over the coming years. The thorny question of financial support for developing countries was raised, and there was agreement to increase the money to help the poorer nations to adapt to climate change. Despite a previous $100 billion a year commitment by 2020 not being met, the richer countries pledged to increase financial support for these countries.

These were good outcomes, so long as nations follow through on their pledges, yet some people have questioned the value of the annual COP process. Tens of thousands of people participated in COP26, and the media coverage was extensive. There is no doubt that it raised awareness of the climate change issue, bringing it into people's homes and encouraging discussion, as do all the COPs. There was also considerable 'direct' action by activists who believe that climate change is an existential issue that requires much more action from decision-makers in governments, industry, and other organisations, and there were some people who simply thought this was a wasted exercise.

The evidence that the COP process can deliver the level of greenhouse gas emission reduction needed to stabilise the climate over the next three decades is not promising, judging by the latest levels of CO_2 measured in the atmosphere. At first sight, this may suggest that the COP process has not been effective, but it is likely that CO_2 levels in the atmosphere would have been higher in the absence of an international process. However, the key point is that the COP process is not as effective as it needs to be, and it is important this is addressed.

A major new initiative at COP26 gives a clue as to what needs to happen alongside this formal process. As indicated above, China and the United States were the two largest CO_2 emitters in 2020; they have also been the largest emitters, cumulatively, in the period 1965–2020. It was encouraging, then, that they reported they had been in bilateral discussions on climate change and had agreed to work together over the next decade to help achieve the target set out in the Paris Agreement. This was a very important initiative, assuming there is meaningful follow-through with action, because these countries are not only the two major emitters but also the two largest economies in the world and fierce commercial competitors. Encouragingly, it does suggest a way forward whereby the largest emitters in the world can and should collaborate outside the formal COP process; the potential benefits to the world are huge.

Interestingly, there are forums whereby these countries can come together and agree to act on climate change, unencumbered by the need to reach a consensus with a much larger number of countries that attend the COPs and away from the glare of the media and the public. For example, five of the highest emitting countries – United States, Japan, Germany, the United Kingdom, and Canada – are members of the Group of 7 (G7) major economies; perhaps more importantly, these countries along with China, Russia, India, and Brazil, are members of the G20. This, then, offers ample opportunity for countries to discuss climate mitigation measures alongside the thorny issues of trade, competition, and financial support for poorer countries.

The climate is changing, and the evidence that we are entering a more challenging period continues to grow. Global land-sea temperatures reported show a steady increase over the past 50 years; the temperature increase is currently almost 1°C higher than the average temperature in the period 1950–1980. These record global temperatures have resulted in shrinking polar ice sheets and rising sea levels, extreme weather, including intense storms, and more frequent droughts and wildfires. Water resources are affected: in some areas, too much rainfall in a short time causes floods, while in other parts of the world, too little rainfall is putting enormous strain on freshwater resources. The latter is projected to get much worse in the future as temperatures continue to rise through 2050.

1.6 Climate change implications for water resources

Concerns around the impacts of climate change have centred on rising temperatures and changing weather patterns, evidenced by highly visible short-term events such as wildfires, intense storms, and flooding; their effects have been devastating, with considerable physical destruction to the environment and significant loss of human life. Longer term drought conditions and the availability of water have received less attention, yet the figures are alarming, with a significant portion of the world population lacking access to clean freshwater for some periods during the year.

The United Nations estimates that global water use has increased by a factor of six over the past 100 years and continues to grow at a rate of about 1% per year. Available surface water resources at the continent level remain relatively constant but many countries are already experiencing water scarcity conditions. Almost all countries in a belt around 10°–40° North, from Mexico to China, including Southern Europe, are affected by water scarcity, together with Australia, Western South America, and Southern Africa in the Southern Hemisphere.

It is perhaps strange to be worried about water resources when over 70% of the world's surface is covered by water. However, the freshwater resources on which we rely make up just 3% of the total, and most of this, being ice, is not readily accessible. The World Bank reports the estimated annual freshwater withdrawals as a percentage of the freshwater renewals by country. A simple analysis shows that the average value of withdrawals has risen from around 50% in 1992 using the available data from 120 countries to almost 70% covering 178 countries in 2018; there are a significant number of countries exceeding 100%.

The United Nations suggests that water scarcity occurs when annual freshwater withdrawals amount to greater than 25% of the renewable water resources; on this basis, 60 countries around the world currently suffer from water scarcity. A more granular analysis is possible by considering three bands: those countries that do not suffer from water stress are those in which annual freshwater withdrawals amount to less than 20% of the renewable water; countries suffer from water scarcity or severe water scarcity if withdrawals amount to 20–40% and greater than 40% of renewable resources, respectively. Using the most recent World Bank data available, 43 countries suffered severe water shortages in 2018 and 27 suffered water shortages; the remaining 108 countries have freshwater supplies to meet their current needs.

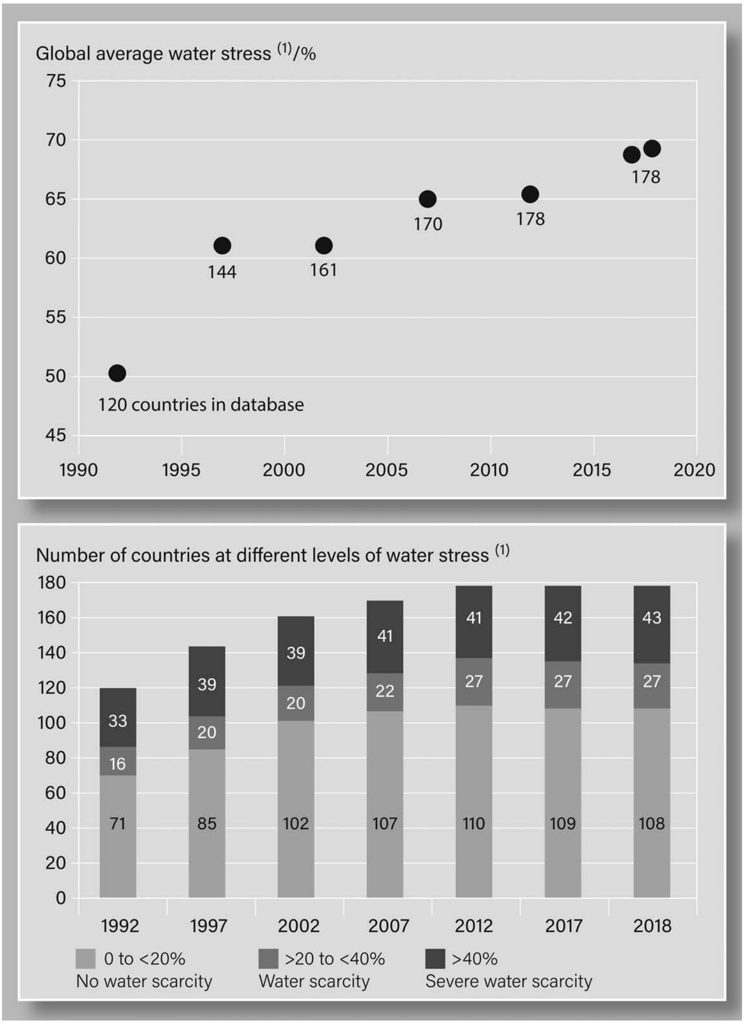

Figure 1.2 Level of water stress increasing across the world

Source: World Development Indicators, World Bank, 2022.

Note: (1), Level of water stress is defined as freshwater withdrawal as a proportion of available freshwater resources.

Crucially, these metrics mean that an estimated two billion people worldwide, or a quarter of the world's population, do not have access to safe drinking water, and about half of the world's population experiences severe water scarcity for at least part of the year. These numbers are expected to increase as the population continues to grow in the period to 2050 and climate change impacts become more severe. Water scarcity is a challenge for both developed and developing countries on all the inhabited continents of the world. Desalination is a technological solution that can be readily applied in all regions of the world.

1.7 Desalination is an essential provider of freshwater

Freshwater resources are under pressure. Current global water withdrawals, at about 4,600 km^3 per year, are near maximum sustainable levels, while the volume of groundwater extracted currently amounts to about 960 km^3 per year globally and is predicted to rise to 1,100 km^3 per year by 2050; a third of the world's biggest groundwater systems are already under pressure.

The water industry is working hard to meet the increasing demand for freshwater: through improved management of water resources, water recycling, reuse and harvesting, greater efficiency in use, and improvements in the water supply and distribution infrastructure. There has also been good progress in the development and deployment of desalination technology, the act of removing salt from saltwater to produce potable water, that is, water fit for human consumption.

Desalination is not a new technology, having been exploited by Greek sailors who boiled saltwater and collected the steam to produce drinking water over 2,000 years ago; sailors continued to use this method for centuries. The world's first recorded commercial desalination plant was built in Malta in 1881 to service the needs of the Tigne barracks, and a distillation plant was built on the island of Curaçao, in the Netherlands Antilles, in 1928 with a capacity of 60 cubic metres (m^3) per day.

Technological developments gathered pace. In the 1930s, the first desalination plants were built in the Middle East. These countries were rich in oil but poor in water resources, so they used their newfound oil wealth to build desalination plants. The first Multi-Effect Distillation (MED) plant was built in Saudi Arabia; this technology involved a low-temperature thermal process of obtaining freshwater by recovering the vapour of boiling seawater, not unlike the Greek sailors two thousand years earlier but using much more efficient technology and on a larger scale.

The 1950s also saw some significant developments: The United States Congress passed *The Saline Water Act* in 1952 to provide federal support for desalination, and the first Multi-Stage Flash Distillation (MSF) plant was built in Kuwait in 1957. In this technology, hot water was stored at low pressure in

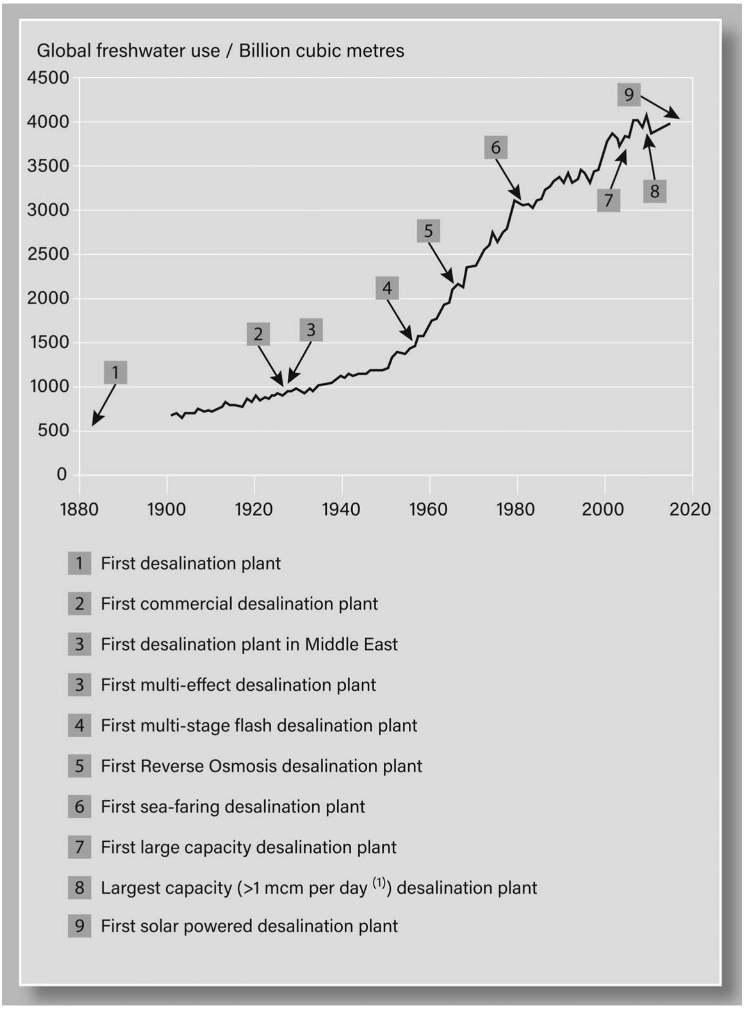

Figure 1.3 Milestones in the development of desalination

Sources: Freshwater Data from Water Use and Stress, Our World in Data, 2018; Milestones from Desalination Plant History, Preceden, and Does Size Matter? Meet Ten of the World's Largest Desalination Plants, Aquatech, 2021.

Note: (1), mcm is million cubic metres.

a large chamber, with the low pressure causing the water to change instantly to steam, which was then condensed into drinking water.

One of the first seawater desalination demonstration plants in the United States was built at Freeport, Texas in 1961. This was followed by the world's first commercial Reverse Osmosis (RO) plant, built in the state of California, in the United States in 1965. RO is a process of removing salt and other contaminants from saltwater and brackish water by running the water through a membrane with 1,000s of microscopic pores. When the water flows into the membrane, the salt and other contaminants are captured in the pores, with potable water passing through. This plant produced just 22 m^3 per day of freshwater from brackish water.

The MED, MSF, and RO concepts are now the three mainstream desalination technologies. Over time, the scale of the desalination plants increased significantly. The first of the very large capacity plants was built in Ashkelon, Israel, in 2005, producing 165,000 m^3 per day using RO technology; this was followed in 2009 by a similar plant, this time producing almost 400,000 m^3 per day in Hadera, and in both cases, RO technology and feedwater from the sea were used. The largest plant of over 1 million m^3 per day, was commissioned at Ras Al Kahir in Saudi Arabia in 2014 using a combination of RO and MSF technologies.

The industry continues to evolve, both in terms of scale and efficiency and by using renewables to supply its energy needs. The world's first large scale solar-powered desalination plant was commissioned in 2017 in Al Khafji, Saudi Arabia. The plant's capacity is 60,000 m^3 per day, enough to supply a city of 150,000 people.

The global footprint of the desalination sector is impressive, with about 20,000 desalination plants built worldwide in the period to 2020, of which about 16,000 are operating today. Many more are planned in the future, and the expectation is that the number of desalination plants around the world may double in the next 25 years.

Desalination, then, is a major industry supported by a global supply chain but receives relatively little attention compared to, say, developments in the renewable energy sector. In the following chapters, the context for desalination will be discussed, beginning with the drivers of water demand and the natural water resources available. The desalination technologies will be described and the attributes of the 'winning' technologies highlighted. Energy and environmental impacts are key issues for the sector, and these are discussed along with possible future developments in these areas.

The role that desalination plays in ten country case studies in water-scarce regions of the world is discussed and serves to explore different dimensions of the technology. The further evolution of this sector in water provision in the period to 2050 and the environmental consequences are explored using scenario analysis.

Summary key points

- Climate change is the defining issue of the 21st century and will make the world much more challenging. Governments and the water industry around the world will need to address increasing water scarcity and the provision of potable water.
- The greenhouse effect associated with our atmosphere is a natural phenomenon that has kept the earth's environment stable and habitable for thousands of years.
- Human activity has led to rising concentrations of greenhouse agents – CO_2, CH_4, N_2O, and SF_6 – enhancing the greenhouse effect. This is leading to higher global temperatures and changes in climate patterns around the world.
- The evidence that our climate is changing is clear and predictable – an increasing frequency and scale of extreme weather events, longer droughts, and greater aridification – but efforts so far have been less than needed to limit rising global temperatures.
- Climate change requires action in the form of mitigation to limit the scale of the problem and adaptation in those regions that are already or will be under considerable stress in the coming years and decades.
- Water resources in some regions are already under extreme pressure, made worse by climate change. Better management of renewable resources, innovation, and new technologies will help alleviate the problem.
- Desalination is an important technology that has emerged in the mainstream water industry over the last few decades. It is playing a very important role in water-stressed regions around the world, relieving pressure on renewable and groundwater resources.