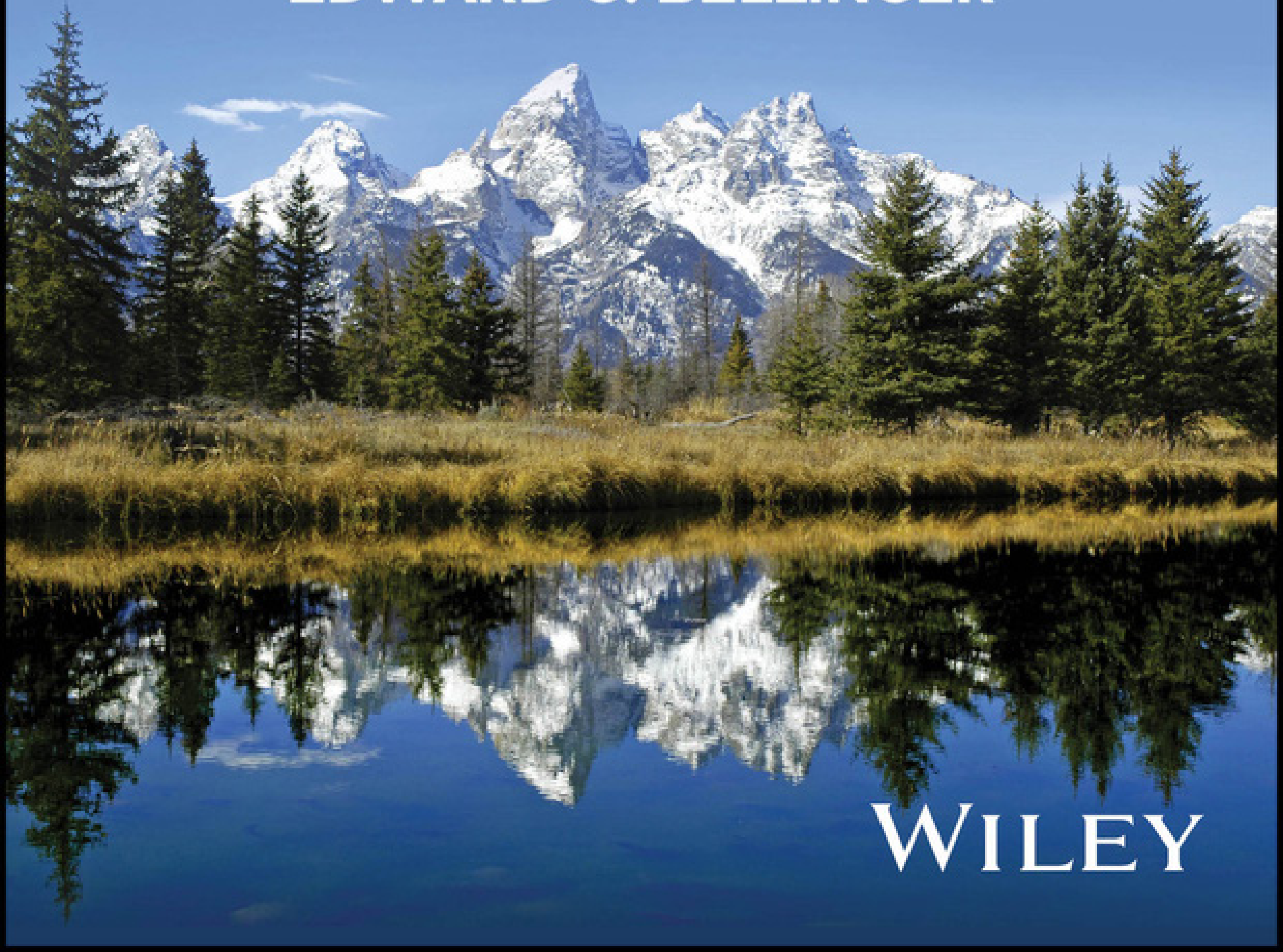
# WATER

## OUR SUSTAINABLE AND UNSUSTAINABLE USE

EDWARD G. BELLINGER



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# Contents

## About the Author

I am a graduate in Biological Sciences from the University of London. After graduating, I studied for a PhD at the Royal Holloway College (London University) on algal problems in water storage and treatment, investigating the causes of problems and their potential solutions at various waterworks of the Metropolitan Water Board (now Thames Water). On receiving my PhD, I was employed by the Metropolitan Water Board, which enabled me to gain much practical experience. In the early 1970s, I joined the Department of Engineering at the University of Manchester, lecturing on Public Health Engineering, and was also involved in setting up the Pollution Research Unit. This group started a master's degree course in Pollution and Environmental Control, probably the first in the United Kingdom, the format of which was followed by many other universities. In 1991, I accepted the post of Professor of Environmental Sciences and Policy at the Central European University (CEU) in Budapest (now in Vienna). This period involved travelling and presenting occasional lectures to students in many countries, including the former Soviet Union. I was also an occasional consultant for the United Nations, working with the World Health Organization and the International Atomic Energy Association, monitoring various water- and sanitation-related topics that involved travelling to different countries in Africa, Central and South America, the United States of America and Canada. I also worked with the UK Water Industries Training Board, running courses on different aspects of reservoir management and water and sanitation treatment for several UK Water Authorities. I was invited to become a member of the UK Department of the Environment Standing Committee of analysts, which was responsible for producing a series of 'Blue Books' on biological and chemical analytical methods for water. I have published several books on freshwater algae, water pollution control and the impact of climate and water on agriculture in the former Soviet Union as well as numerous scientific papers on these subjects. I am a Fellow of the Chartered Institution of Water and Environmental Management and a Fellow of the Royal Society of Arts.

The aim of this book is to provide an overview of water quality issues and what can be learned from the continuing history of water use in societies from ancient times to the present day. I also cover the main treatment methods currently being used. I have fully documented each chapter so that readers can follow up on any of the specific topics covered.

Our needs and the needs of ecosystems involve multiple pathways for water, which are still being added to. Some are changing and evolving, although others are constant. We can always learn from past experiences, and it is hoped that this will provide a basis for readers in their future work with water and in the water industry.

# Preface

Our perception of water quantity and availability largely depends on where, in geographical terms, we live. If you live in a semi-arid or arid country or certain regions of some developing countries, you will certainly have a different approach to water use and treat it with more care when compared with a developed country with an established infrastructure for collecting, storing, treating and supplying water to its residents where water is taken more for granted. This often results in water being treated as an infinite resource at least from the point of view of humans. It is essential that all societies, both developed and developing, have a better understanding of the key role water plays. Water is essential to all life on this planet. There is no substitute for water in our lives and our requirements for living.

Humans need water either directly or indirectly in all sections of their lives, including our individual bodily requirements as well as the needs of society as a whole. We need it for the production of food, in food preparation, sanitation and waste disposal as well as economic and industrial activities.

Currently, this planet has an environment suitable for a large variety of living organisms found here. This has taken millions of years to evolve, and the essential components, including water, need to be used and managed properly. What we must realise is that water resources are finite and cannot be managed for humans to the exclusion of other organism's needs. Earth has evolved an environment suitable for life as we know it, and this variety of life in turn helps maintain a healthy environment for us, including a suitable atmosphere with the right proportion of oxygen and a suitable climate and temperature. Without these natural ecosystems, the environment would change for the worse. No one group of organisms should command right to an unlimited supply of water and other resources at the expense of others. All resources are finite, although some, e.g. certain minerals, are currently present in adequate amounts for human needs. What humans must realise is that available water is a key finite substance, and human needs cannot override all other needs without greatly modifying or even destroying the life systems on this planet.

Water resource management is being made both more difficult and more urgent because of the rapidly increasing human population and their increasing demands for more water. The aim of the leaders of countries is to improve the standard of living of the populations in those countries. Unfortunately, this also results in their expectations rising and inevitably them using and demanding access to more water for both their households, with things such as washing machines, baths and showers, and for gardens, swimming pools, parks and golf courses. Some municipalities also use water to wash streets. All of these factors not only increase the consumption of water but also increase the amount of wastewater to be treated and disposed of.

Groundwater reserves are being seriously depleted in some areas as is the storage capacity for water in reservoirs and the summer flows in rivers, all of which affect not only the reserves available to humans but also natural ecosystems on which we rely. Wetlands that help cleanse water draining through them are being destroyed worldwide in response to the need for more agricultural land. In addition to these impacts on water availability, our economic and industrial activities are gradually changing the global climate by causing global warming. The immediate effect of this is on the hydrological cycle and will probably result in more droughts and extreme storm events as well as some more subtle events. What is clear is that all communities and water users will need more informed management of water resources and their use by all aspects of society for communities worldwide to survive. Unfortunately, the required holistic view of water management frequently does not exist, with the responsibility being divided among many departments of government. As water is needed for all aspects of society, all users and user groups, including NGOs and local councils, must understand its management and have an input into the management strategies, including ways in which water use can be modified to minimise waste.

In this book, I have stressed the importance of good safe water in preventing disease and generally improving health as well as providing food and sustaining ecosystems. It is also important to have an understanding of the technologies associated with a clean water supply and the safe disposal of waste as well as the potential problems that will occur if these control measures are not followed. It is also important to understand that the technologies involved cost money to build and run, and although governments can help with capital costs, clean safe drinking water and suitable waste disposal will have a cost to users. All parts of society and industry must realise that their actions impact water quality. We must understand that you cannot just turn on a tap and expect there to be an inexhaustible supply of water. The hydrological cycle is global, and individuals do have a cumulative effect on this global cycle. This is why a sustainable future can only be achieved if everyone understands the role of this vital but finite resource, and that the technology involved in its management is quite complex. This book is based on my work with the water industry both here and abroad, and it is concluded that the basic principles are true for all countries.

## Acknowledgements

Firstly, I would like to thank my wife PAM for her patience, encouragement and understanding during my writing of this book. I would also like to thank Neil Porter for his help with scanning figures and other electronic issues.

I would also like to thank the Thames Water Authority, with whom I first worked, although they were then called the Metropolitan Water Board and Severn Trent Water for permission to use some of their training figures. I have also worked with most of the other UK water authorities and would like to thank them for their help and experience with their technologies. I have always enjoyed working with them and many others working in the water industry both here and in many other countries, which enabled me to gain experience with a wide range of problems and solutions in water use and management. I would also like to thank Wiley-Blackwell staff for their help with occasional publication issues with the text.

# Introduction

Water is an essential component of all living things including humans. The poet W.H. Auden said 'many have lived without love, none without water'. Water is the most widely occurring substance on the surface of this planet, and living cells depend upon it. We not only contain large amounts of water, about 70% of our body weight, but it also provides a medium for the passage of materials around our bodies. Ripl (2003) described water as 'the bloodstream of the biosphere' because of its importance as a major transport route for essential chemicals. It is a naturally occurring solvent capable of dissolving, to a greater or lesser extent, a very wide range of chemicals, which is perhaps its most important biological role (Sharp 2001). This includes both small molecules, such as nitrates, phosphates and sugars, and very large molecules, such as proteins and nucleic acids. Virtually, all biologically important chemical reactions need to be in solution to work. Water is also essential for the provision of food, as a drink, and is also needed for hygiene as well as providing a large amount of energy that we use. Water moves over the surface of this planet as well as through the atmosphere in a continuous cycle that is partly driven by gravity and partly by energy from the sun. This movement is called the *hydrological cycle* (see Chapter 4). This cycle involves water as a liquid, a solid and a gas. It is needed to sustain the myriad of ecosystems and provide the ecosystem services used by human societies (Jimenez-Cisneros 2015). Most of the water on this planet is saline and occurs in the oceans. Only a small amount is present as freshwater.

Water does not stay in any one state or location indefinitely. It does, however, remain in each location, or reservoir, for different lengths of time before moving to another reservoir either in the same state or a different one. For example, changing from liquid in a lake to water vapour in the atmosphere by evaporation. The amount of time that the water stays in any one reservoir before moving to another is called its residence time, typical examples of which are given in Chapter 4. From these examples, it is clear that water can exist in different forms and that availability for human and ecosystem use will vary greatly.

Water has many key properties that affect its behaviour and are also exploited by organisms. These properties both cause and allow water bodies, especially standing waters, to behave in certain ways, and these properties have been capitalised by many aquatic organisms to their advantage and moulded their behaviour (see Chapter 6). As land plants including trees rely on soil as a main medium in which they grow, although they require soil moisture for mineral transport, fish and aquatic plants rely on these water properties.

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Many aquatic organisms are equally dense or less dense than water that is then also used for physical support. Pure water is very transparent so the upper layers of a water body have reasonable levels of light intensity. The fact planktonic cells are continuously bathed in a medium with dissolved chemicals as well as being supplied with solar energy is only good for growth if they are all in the correct quantities. If some are present in excessive amounts, e.g. the major nutrients (see Chapter 6), it can lead to major imbalances in the biological response such as excessive growths of harmful algal blooms causing severe water quality problems and be dangerous for human health. Atmospheric moisture and its circulation play an important role in the movement of heat energy across the planet. Water movement is also important in shaping our landscapes by erosion, weathering of rocks and transporting minerals. Its interaction with the whole biosphere results, if the patterns of change are regular, in a self-supporting system (Ripl 2003). Human societies have traditionally developed close to readily available supplies of water such as rivers, lakes and springs. In the past, and even today, water has provided food in the form of fish and has been harnessed for that purpose. It is now commonly used for recreational activities as well as being significant in a number of religious beliefs and activities. Unfortunately, human interventions in the system can lead to destabilisation of these processes so that whole sectors of the system can be disrupted. It must always be remembered that this planet can support life as we know it because of the biosphere that is composed of many different ecosystems maintaining an environment suitable for human life. Green plants capture solar energy and absorb carbon dioxide from the atmosphere and with the aid of water produce more complex organic molecules, and as a by-product, pass out oxygen and water vapour into the atmosphere through the process of photosynthesis.

There are potential problems concerning the uneven distribution of freshwater over the surface of earth especially as human population growth rates are in regions of the world where water is, or will soon become, scarce and also suffer from low incomes making them less able to cope with future shortages. Some areas are naturally water abundant whilst others are water scarce or arid. With human populations rising globally, it is not just a question of sufficient water for basic human needs but also enough for food production. Many countries have the aspiration of being self-sufficient for food which means continuous increases in water demand. Water is also needed for economic activities. Although the problems of global climate change have come to prominence in the past few years, the problem of providing safe, adequate freshwater and proper sanitation to many people has been with us, and still is, for some time, and with some organisations it is still at or near the top of their list of problems of human quality of life. Water and climate change are inextricably linked together.

For many thousands of years, human settlements have used water and have developed technologies and strategies, but this has had only local impacts and did not have a wider effect on the hydrological cycle (Chapter 1). Since those times of small local communities when the view developed, at least in northern European countries and the northwest United States, water supplies were inexhaustible and, at least in the case of large rivers and the sea, they could be used for waste disposal because there would be infinite dilution that would render the waste harmless. In the past centuries, however, the global human population has grown exponentially and with it so has demand for more water per individual. With larger populations and greater industrial activities over the past hundred or more years, this has ceased to be true and anyway infinite dilution does not occur.

Warnings about water quantity and availability have been around for many years (Falkenmark 1997 and Chapter 4). Unfortunately, our attitude started to change with the onset of the industrial revolution. This new post-Holocene era has been termed the Anthropocene (Lewis and Maslin 2015). This was marked by both a rapid increase in population and an ever-increasing exploitation of natural water and other resources. Earth support systems are now being threatened. The IPPC (2007) has clearly pointed out the impacts of human activity on global climate systems. It is reasonable to assume that, in pre-Anthropocene times, as long as resource use was kept within sustainable limits, the stability experienced in the Holocene would continue for many thousands of years (Berger and Loutre 1991). If these limits are exceeded, then major changes could occur threatening human existence. It is therefore important to understand what these limits are.

Rockstrom et al. (2009) introduced the concept of 'planetary boundaries'. They describe these boundaries as 'human determined values of the control variables set at a safe distance from a dangerous level'. In other words, where possible we should determine the maximum limit for human exploitation of any particular resource and limit our use of it to be safely within that limit. The problem arises that our scientific knowledge of these boundaries and our ability to properly quantify them is often imperfect. Rockstrom et al. (2009) acknowledged the difficulty with some of these complex systems of assessing the effects of mechanisms, e.g. feedback mechanisms and self-regulation, in natural systems, and the timescales involved. Rockstrom et al. identified nine planetary boundaries.

Although because of the inter-relationships of all planetary systems consideration should be given to all of these when considering the hydrosphere, climate change, biogeochemical flows, including the nitrogen and phosphorus cycles, freshwater use, land system changes, chemical population in general and biodiversity loss will be examined in more detail in some of the following chapters. The main process of interest in this volume is global freshwater and factors that have a direct impact upon it. Shiklomanov and Rodda (2003) point out that human activities are the main driving force for change in global flows. They also have an important influence on the seasonal timing of cloud formation and precipitation. Molden et al. (2007) have estimated that 25% of the world's river basins run dry before they reach the sea because of over abstraction. Human alterations to the hydrological cycle affect many other areas of activity including food production, human health, climate, and ecosystem functioning. These adverse effects also impact human livelihoods. Postel (1999) estimated the upper limit for blue water resources to be between 12 500 and 15 000 $km^3$/yr. Actual physical blue water scarcity is reached when withdrawals exceed 5000–6000 $km^3$/yr (Raskin et al. 1997). Rockstrom et al. suggest a planetary limit of about 4000 $km^3$/yr. If this is exceeded, there could be major perturbations or even collapse of other systems.

Land use change has a major effect on the hydrological cycle as well as local ecosystems and biodiversity. Continued expansion of crop lands will have increased impacts on water quality, run-off, floods, and overall river flows. A planetary boundary of no more than 15% of ice free land could be used for agriculture. If this boundary were to be followed, its implementation must take into account local conditions so that the most productive lands were used for crop production and other less productive land if suitably used for forests and other ecosystems.

Water quality is a continuing issue and has been throughout the Anthropocene. Deteriorating water quality severely reduces the quantity of useable water. Unfortunately, one side effect of human industrial, agricultural and medical progress has been that, as well as more traditional pollutants such as sewage, heavy metals, pesticides, etc., many new compounds are finding their way into waters. These affect both human and ecosystem health. Initially, this was confined to local events, but now some are having global effects, for example microplastics. Many countries, especially in the developed world, have placed restrictions on the use and disposal of many toxic/undesirable chemicals in the aquatic environment. These restrictions are usually made without taking into account the cumulative global impact when viewed additively on a global scale. There is thus a need for setting a planetary boundary for these chemicals. Difficulties arise with this because of our imperfect scientific knowledge on individual chemicals but perhaps more importantly what the effects are with combinations of them. This is not surprising when one realises that there are an estimated 80 000–100 000 chemicals on the world's markets. The planetary boundary concept suggests two approaches. The first concentrates on persistent chemical pollutants with a global distribution, and the other is for chemicals having unwanted long-term and/or large-scale impacts on living organisms. Examples of each of these are discussed in Chapter 6. Currently, no definitive boundaries have been set. It should be remembered that, although Rockstrom et al. defined nine planetary boundaries, these do not act independently but impinge upon each other so that a significant change in one will impact several others. An example of this is the decline in tropical rain forests, which not only affects biodiversity but also carbon sequestration, the hydrological cycle and ultimately the climate. Whilst the concept of planetary boundaries has its uses for developing strategies, there are objections to applying all nine globally. Some, it can be argued, only apply at a local or regional level. Moreover, six of the nine do not have planetary biophysical thresholds in themselves. Global climate change (of which ocean acidification is a part), ozone depletion (which may have been partly, at least, addressed with the greatly reduced use of chlorofluorocarbon gases) and phosphorus concentrations in freshwaters whose threshold point is quite probably a long way off may still be regarded as having global effects. Other tipping points may not be global and are at the most regional. This being so, it is difficult to set global boundaries.

Answers to the above and many other questions have been discussed by many international organisations, and there have been a number of international conferences during the past 50 years, aimed at paving the way to sustainable water management. In the year 2000, the United Nations set out a series of goals covering all aspects of human well-being, including many of the points raised in the previous conferences. These were to be achieved within the following few decades. For safe drinking water and sanitation, targets were set to halve the number of people without proper access to both by 2015. Although some progress has been made, unfortunately much more is still needed. Many of the millennium development goals involve the supply of proper drinking water and sanitation before they can be achieved as water impinges on areas such as health, food supplies and schooling. In the latter case, many children are unable to attend school because of suffering from waterborne illnesses such as diarrhoea. Solutions require an integrated approach with understanding and cooperation from all sectors of government and also all stakeholders, but water has often not been the highest priority in many governments as focus being placed on economic development. Consideration of sustainable water use must go beyond the particular needs of one particular activity and must take into account the way that water, as a substance, behaves on this planet. In previous years, water was viewed as a largely local or regional issue and had a narrow sectoral approach often with the responsibility of a single government ministry whereas all ministries need to be involved. The approach must look beyond just human needs, but also allow for the needs of ecosystems as these are the life support systems on this planet. It is often difficult to break away from this old approach, but it must be done and coordinated approaches must be adopted. With the expansion of world trade, we are sometimes referred to as a global village, and water is now of global concern and is, to an increasing extent, a global commodity. Part of the realisation for this all embracing approach has come from the concept of the food–energy–health–environment nexus (nexus being the complex series of connections between these sectors). The global aspect is allowing communities with water scarcity to survive based upon both real and virtual water (see Chapter 4). Water thus transcends the concept of being a single responsibility, which in some respects it is, and becomes a vital consideration for all sectors as its proper management is of benefit to all. The hydrological cycle and its interaction with humans is extremely complex. Setting goals requires trade-offs between political and economic requirements and, importantly, ecosystem needs. General agreements on limits to water use are extremely difficult to obtain. It is certainly true that, until water is managed sustainably both locally and globally, global improvements in human well-being will be difficult to achieve. It would certainly help if all users had a better understanding of the complex technologies involved in providing clean safe water and disposing safely of waste without destroying ecosystems. All of these functions, together with their maintenance, come at a cost that must be shared, to an extent, with the users. The cost of drinking water and sanitation must not be prohibitive, but people must understand that there is one and both have to be contributed to by the user. It is also important that the public understand various ways in which water can be saved and waste can be reduced, which if followed will save both the consumer and the water provider money. This would then be a win/win outcome. Certainly, in developed countries, adequate water supplies and sanitation tend to be taken for granted by the public, but with an increasing global population and their demands together with the potential effects of climate change, which is likely to still be there for several decades, careful use and general conservation measures need to become automatic. Without this approach, water shortages in the future will be inevitable.

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# 1

# Our History with Water: What Can Be Learned from Past Water-based Communities

Water is an essential resource to humankind and all other living things. Because water is essential for life and no life can exist without it, human societies have tended to live and develop their communities within easy access to freshwater. When this is not available, nomadic people would migrate from one source to another, often seasonally, to find suitable supplies and food for themselves and their animals. Some animals were kept for food, meat, milk and bones for tools and others for their skins which were used for clothing. When settled agriculture developed, water was required on a more consistent basis. Water was not always continuously available so then, as now, they developed techniques for water harvesting, conservation and its transport. This became especially important as populations grew and larger communities developed, both of which needed larger supplies. Although larger structures like the Parthenon and Colosseum are widely admired, the driving forces behind the success of these and other ancient communities was the development of technologies both to provide water and sometimes to harness it for power. These advances have not been given enough attention by historians who tended to concentrate upon their politics and wars. Indeed, most historians and economists often assume that societal progress using technology only became important after the middle ages. The wealth and success of many ancient civilisations was, in fact, based upon the control of water using hydro-engineering and the invention of new technologies. Many ancient civilisations needed to use water sustainably to survive, so developed techniques to both support their needs and harmonise with nature. Sometimes this led to conflict between different communities, especially where water resources were limited.

It is worthwhile to consider some of these techniques and, in some cases, perhaps use them in modified forms to solve some present-day water issues particularly in semi-arid climates and developing countries. Although initially the management of water concentrated on controlling it for irrigation, as time passed water power started to be harnessed and used for a number of other uses, including grinding grain, driving bellows, grinding mineral ores, operating forge hammers and saws (Wilson 2002). Although precise details of water technology's impacts on the overall economy of ancient countries are not quantified, there is some information on the huge investment that was for olive oil production in Africa and Tripolitania (Mattingly 1988). There is evidence of large investments in aqueducts for transporting it and cisterns for water storage which were used for irrigated agriculture for fruit and vegetables, both for supplies to Rome and export. This sort of evidence

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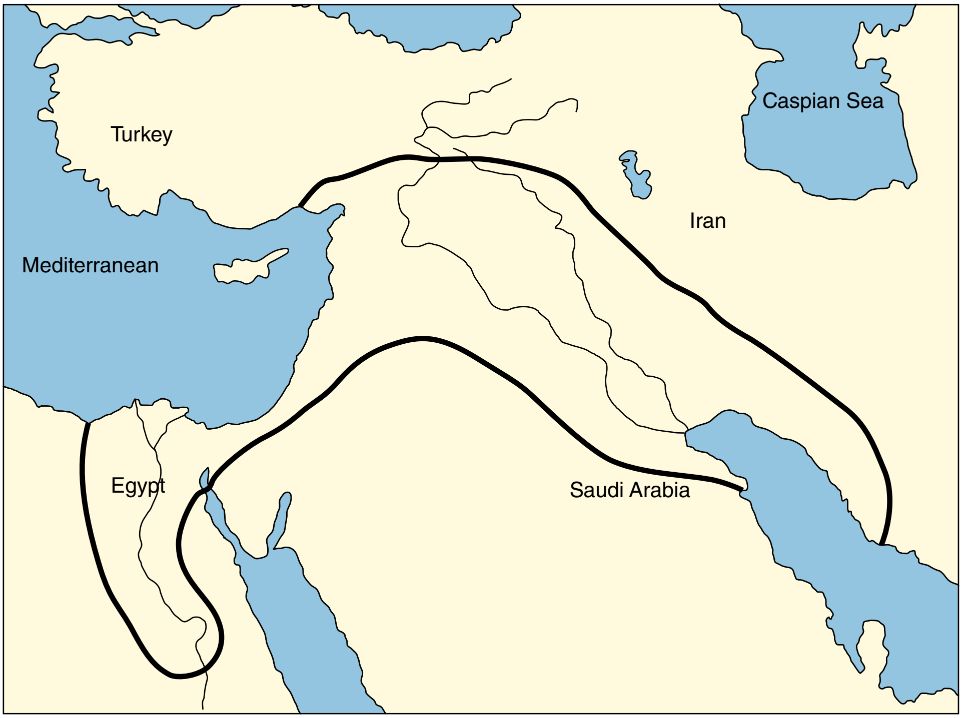


**Figure 1.1** Map showing area of the Fertile Crescent.

illustrates the importance of water management and the amount of investment ancient societies were prepared to make to boost their economies. The region between the Rivers Tigris and Euphrates, part of which is in present-day Iraq, was where we believe settled agriculture developed and was known as the 'Fertile Crescent' (Figure 1.1). Agriculture also developed in other parts of the world, including Egypt, China and India where good water supplies were available. Water supplies were essential both for the populations and their economies, and if they failed starvation in parts of their populations was not uncommon. Early conurbations occurred in Jericho (8000 to 3000 BCE) and Egypt (3000 BCE). The first more intensive urbanisation occurred around inventions is covered in this chapter, and only selected example years to demonstrate the breadth of knowledge, engineering and invention of these societies are discussed below.

## Mesopotamia

Settled agriculture was probably developed by people selecting seeds from plants that gave better yields, and some could be saved and used for planting and growing into new crops that gave higher yields. They also selected the best animals for breeding as well as for meat and milk production. This was basically the process of domestication. When settled agricultural communities developed a little over 8000 years BCE (Blockley and Pinhasi 2011), water was required on a more constant basis for raising their crops and livestock. As populations grew water was needed in ever larger quantities and its continued availability was essential for the economic and political development of those civilisations. One of the best known was that developed by the Sumerians, Assyrians and Babylonians in the 'Golden Triangle' between the rivers Tigris and Euphrates and extending up to the Upper Nile in which is now part of Turkey, Syria, Iraq, Israel, Palestine and down to Egypt. The river Euphrates, which is 2800 km long, originates to the north of Lake Van and winds its way down to the Syrian plateau. The Tigris (1950 km long) rises in Armenia near Mount Ararat and flows south-east roughly parallel to the Euphrates but does not merge with it until 100 km north of Basra to form the Shatt-el-Arab that eventually flows into the Persian Gulf. Mesopotamia is divided into upper and lower parts, the upper being mainly a piedmont zone below a mountain zone and supports dry agriculture and the lower is an alluvial plain. It is in this plain that settled irrigated agriculture developed. Across the plain, the rivers tend to flow between raised banks above the plain which, when the river banks are breached, form lakes and marshes. This crescent-shaped area is known as Mesopotamia and called 'the cradle of civilisation' (see Figure 1.1). People migrated from the highlands where the agriculture was rain fed to settle in the lowland plains where the soils were often quite rich. They became known as Sumerians. The area between the rivers was, however, prone to cycles of flood and drought which did not correspond to the cropping season. The flood periods tended to be April and June. In order to properly utilise the land, the Sumerians had to learn how to overcome the vagaries of climate, tame the floods and manage the droughts. Here, however, there were good soils, and the water began to be managed around 6000–7000 years ago for human and a little later for agricultural use. To overcome the uneven distribution of water supplies with time, they constructed a network of canals and reservoirs to supply water to the arable fields at the correct times. The provision of managed water extended the crop-growing season and increased yields. This also encouraged clearing of any suitable land of its natural vegetation for use in agriculture. There were strict laws governing the use of the water, the operation of the canals and reservoirs to regulate their use so as not to affect other water users and their crops. It is thought that writing was invented in Mesopotamia in the form of inscribed clay tablets. Agricultural yields began to increase faster than the population's needs leading to surpluses that could be used for trade. This resulted in the waterways being also used for transporting goods. As this use increased, there was a need to raise the river banks to allow increased water transport but this increased the risk of the banks failing, causing flooding as well as affecting local societies. Water use was so essential for human development that if the supply failed in any year people often starved and their economies suffered. In later years, poor crop yields arose not because of drought but through poor drainage of the soils leading to their salinisation. The black rich soils gradually turned white through salt accumulation. As populations grew, so did the development of the number of urban areas. This together with the irrigation needs for settled agriculture led to the development of growing expertise in aspects of engineering hydrology to manage any unpredictability of river flows and their flooding as well as the ability to produce food surpluses and an active food export business creating both wealth and power. The Mesopotamian society was at its peak between the third and seventh centuries CE. The ruling Sassanians were able to expand the hydrological schemes and irrigated most if not all of the cultivated land. It is estimated that this amounted to about 50 000 km$^2$ of land. More than double the area cultivated in modern Iraq with an estimated population of five million (Adams 1962). After the Arab conquest in 639 CE, the population declined as did work on the maintenance of the irrigation system. The estimated silt load carried by the Tigris and the Euphrates was as much as three million tons a day during floods. Much of this is deposited in the flatter parts of the plain where the river velocities decreased and in the irrigation channels. The silt also caused the river banks to be raised resulting in the river being much higher than the surrounding land. This silt in the irrigation channels had to be continuously removed to stop blocking, and this required much labour to keep them flowing. Salt build up gradually became a bigger problem reducing crop yields so that food surpluses were reduced which in turn reduced amounts for export so the wealth of the country steadily declined. There was even a danger of food shortages. By the tenth century CE, tax receipts had declined by 60%. Lack of income then forced the authorities to cut back on labour to do the maintenance. By the eighteenth century CE, revenues had declined by 87% (Christensen 1993). Within the next 200 years, salinisation continued making the area largely unsuitable for agriculture. The problem that arose in this irrigation system is that drainage was not properly allowed for causing the salt to build up. If the canals were not dug out continuously, blockage and reduced flows could require new canals to be built (Mays 2010). The behaviour of the sometimes erratic seasonal flows of both rivers is in contrast to the Nile whose flooding was fairly predictable in time if not entirely by volume. The Sumerians thrived during the period of plenty and developed a number of cities some of which had populations estimated at between 10 000 and 20 000.

There is evidence that the growth and development of the Mesopotamian civilisation was not continuous nor a steady one. Borrell et al. (2015) reported that a period of rapid cooling of the climate in the Northern Hemisphere resulted in a hiatus in development about 10 000 years ago. This interruption in development lasted for a short while before normal conditions returned. The Mesopotamians also developed other engineering technologies including the use of diversion dams, e.g. the Nimrud Dam (Butler 1960). In this, the river water was diverted through the Nahrawan Canal and was used to irrigate a large area of cropland. They also used lifting devices to take water from a river, canal or well for both human and agricultural use. The first were human powered and consisted of a bag and rope strung from a wooden beam with a counterbalance at the other end. These were called a shaduf (Figure 1.2). These were used as early as 2300 BCE. Early conurbations grew in Jericho (8000–3000 BCE), Egypt (3000 BCE) and Harappa in Pakistan (2300–1700 BCE). Other technological innovations included water tunnels and donkey powered chain lifts. More intensive urbanisation occurred around the Mediterranean at around 500 BCE to 500 CE. Historic written and archaeological material is more common for this region and period. In many areas, water was obtained by digging wells. Tapping into groundwater became more elaborate, and underground transport systems for moving this water allowed the irrigation of crops away from surface water supplies. The Sumerians did not need to understand the physics of their systems but by trial and error were able to work out the best ways to operate them. They did, for example, realise that by inflating a bag it could be used as a floatation device to help moving goods along a waterway. Mesopotamia also developed systems for wastewater disposal. Houses were provided with disposal systems (Stordeur 2000). The wastewater was either disposed directly to gutter or canal to pits or

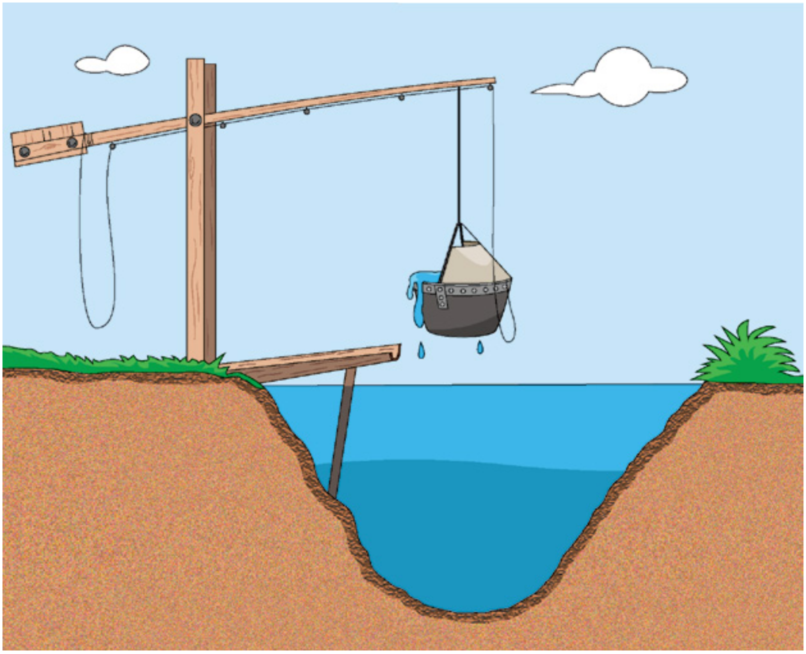

**Figure 1.2** A typical shaduf for lifting water.

ponds in the city and then outside the city walls. Surface drainage systems were also provided in the cities to take away rain and floodwaters. Many houses were provided with toilets and pipe systems to take the waste away.

## Qanats

Systems called qanats are still used in some countries, including parts of the Middle East, e.g. Iran. They were probably developed in ancient Persia over 3000 years ago (Remini et al. 2014). They were developed in semi-arid areas by Arab populations and from there have spread to many other semi-arid areas across the world. This method of harvesting groundwater is given different names in different countries, e.g. foggaras in Algeria, khettara in Morocco and falaj in Oman. Qanats are usually constructed where there is little or no obvious surface water. The technique involves constructing a gently sloping tunnel, sometimes many kilometres long, with a number of wells sunk into it acting as aeration sources (Figure 1.3). This allowed access to the groundwater that could then be used for irrigation. This system has been developed and expanded and used in many countries, mainly those within the zone encompassed by the tropics of Cancer and Capricorn. Water from this source allowed the development of palm oases particularly in North Africa, the Saudi Arabian Peninsula and Iran. Because groundwater has been a reliable source of good quality water, its use has been fundamental for human development in the area. There are several factors that need to be taken into account in constructing and managing a qanat. These include (i) To make sure the water table is adequate for the life of the qanat.

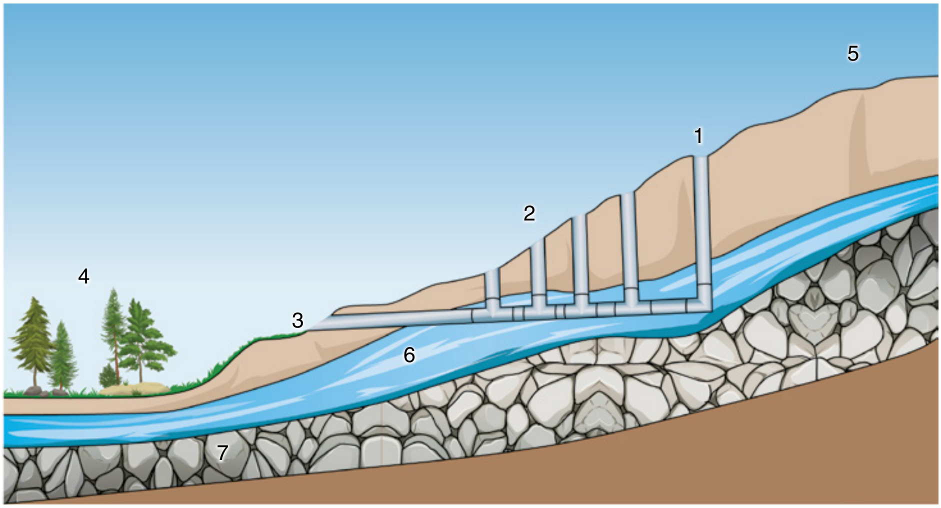


**Figure 1.3** Diagram of a qanat system. (1) Mother well, (2) vertical shafts and air shafts, (3) outlet and main sloping horizontal shaft, (4) irrigated agricultural area, (5) higher land or foothills forming infiltration zone, (6) normal water table and sub-surface water, and (7) impervious bed rock.

Local knowledge of qanat diggers is essential in choice of location. (ii) Knowledge of groundwater recharge is essential in order to manage abstraction rates otherwise artificial recharge may be required. (iii) Recharge can be helped by constructing wide wells, up to 7 m wide and 3–5 m deep which were filled with large stones. These could capture any flood waters that occurred in that area and would help recharge the aquifer. This ancient system is still in use. (iv) Modern techniques such as Geographic Information Systems and remote sensing can help in maintaining and restoring qanats. The use of qanats extended over the centuries to more than 34 countries. There are about 32 000 of these systems in Iran discharging about nine billion cubic metres of water annually. Unfortunately, the use of qanats is generally declining through lack of maintenance and partly because modern wells and pumping are now much cheater and convenient and thus taking over groundwater abstraction. Care is still needed however not to over abstract!

## Egypt

The ancient Egyptian civilisation can be traced back for as much as 11 000 years, and by 5000 years ago, agricultural production concentrated around the valley of the River Nile. This river, which is over 6670 km in length, is one of the longest in the world. It drains about 3 350 000 $km^2$ amounting to about one-tenth of the African continent (Mays 2010). The annual flood lasts, on average, about 110 days starting in June and peaking in late September. The Nile has two branches, the white and blue branches. The white originates in Burundi whilst the blue originates in the Ethiopian Highlands (Shiklomanov and Rodda 2003). The two branches merge at Khartoum (see Figure 1.4). The fertility of the lands adjoining the river depended upon the annual flooding which not only brought water but also deposited considerable quantities of silt which replenished the soils. If the floods