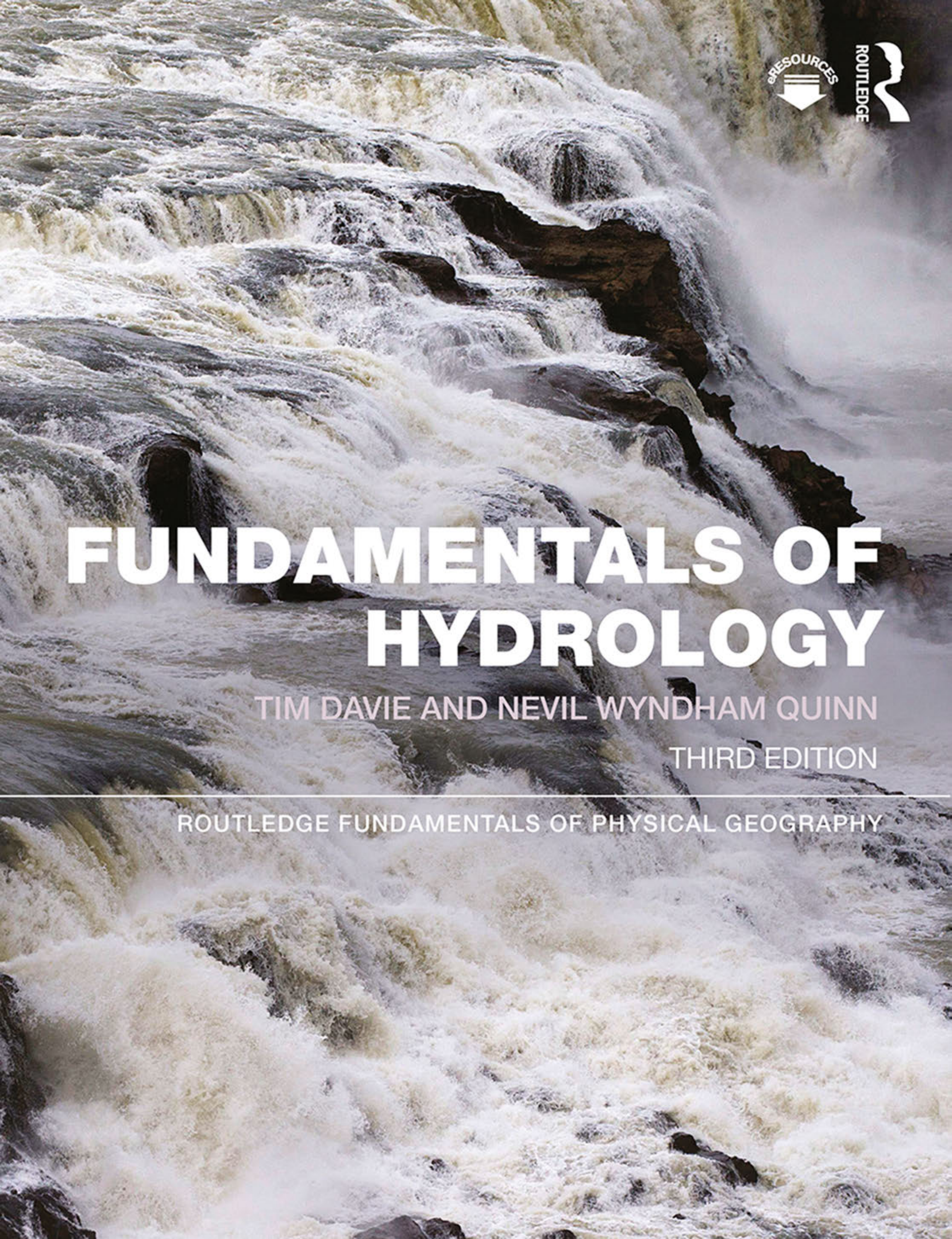

# FUNDAMENTALS OF HYDROLOGY

TIM DAVIE AND NEVIL WYNDHAM QUINN

THIRD EDITION

ROUTLEDGE FUNDAMENTALS OF PHYSICAL GEOGRAPHY

# FUNDAMENTALS OF HYDROLOGY

The third edition of *Fundamentals of Hydrology* provides an absorbing and comprehensive introduction to the understanding of how fresh water moves on and around the planet and how humans affect and manage the freshwater resources available to them.

The book consists of three parts, each of fundamental importance in the understanding of hydrology:

- The first section deals with processes within the hydrological cycle, our understanding of them, and how to measure and estimate the amount of water within each process. This also includes an analysis of how each process impacts upon water quality issues.
- The second section is concerned with the measurement and analytical assessment of important hydrological parameters such as streamflow and water quality. It describes analytical and modelling techniques used by practising hydrologists in the assessment of water resources.
- The final section of the book draws together the first two parts to discuss the management of freshwater with respect to both water quality and quantity in a changing world.

*Fundamentals of Hydrology* is a lively and accessible introduction to the study of hydrology at university level. It gives undergraduates a thorough understanding of hydrological processes, knowledge of the techniques used to assess water resources, and an up-to-date overview of water resource management. Throughout the text, examples and case studies from all around the world are used to clearly explain ideas and techniques. Essay questions, guides to further reading, and website links are also included.

**Tim Davie** is Chief Scientist at the Canterbury Regional Council which controls natural resource management, including water resources, in New Zealand's largest region. Previously he has worked as a research scientist at Landcare Research NZ Ltd and as a university lecturer in Environmental Science and Geography at Queen Mary College, University of London. His PhD, from the University of Bristol, UK, focused on modelling the effects of afforestation on water resources and since then his research interests have been in the fields of land use hydrology (including water quality), satellite remote sensing in hydrology, integrated catchment management, and linkages between science and water policy. Dr Davie is a past president of the New Zealand Hydrological Society and regularly gives guest lectures on water resource management in Universities and to public bodies.

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# FUNDAMENTALS OF HYDROLOGY

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*Tim Davie and*
*Nevil Wyndham Quinn*

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# SERIES EDITOR'S PREFACE

We are presently living in a time of unparalleled change, and concern for the environment has never been greater. Global warming and climate change, possible rising sea levels, deforestation, desertification, and widespread soil erosion are just some of the issues of current concern. Although it is the role of human activity in such issues that is of most concern, this activity affects the operation of the natural processes that occur within the physical environment. Most of these processes and their effects are taught and researched within the academic discipline of physical geography. A knowledge and understanding of physical geography, and all it entails, is vitally important.

It is the aim of this *Fundamentals of Physical Geography Series* to provide, in five volumes, the fundamental nature of the physical processes that act on or just above the surface of the earth. The volumes in the series are *Climatology*, *Geomorphology*, *Biogeography*, *Hydrology* and *Soils*. The topics are treated in sufficient breadth and depth to provide the coverage expected in a *Fundamentals* series. Each volume leads into the topic by outlining the approach adopted. This is important because there may be several ways of approaching individual topics. Although each volume is complete in itself, there are many explicit and implicit references to the topics covered in the other volumes. Thus, the five volumes together provide a comprehensive insight into the totality that is physical geography.

The flexibility provided by separate volumes has been designed to meet the demand created by the variety of courses currently operating in higher education institutions. The advent of modular courses has meant that physical geography is now rarely taught, in its entirety, in an 'all-embracing' course but is generally split into its main components. This is also the case with many Advanced-level syllabuses. Thus students and teachers are being frustrated increasingly by a lack of suitable books and are having to recommend texts of which only a small part might be relevant to their needs. Such texts also tend to lack the detail required. It is the aim of this series to provide individual volumes of sufficient breadth and depth to fulfil new demands. The volumes should also be of use to sixth form teachers where modular syllabuses are also becoming common.

Each volume has been written by higher education teachers with a wealth of experience in all aspects of the topics they cover and a proven ability in presenting information in a lively and interesting way. Each volume provides a comprehensive coverage of the subject matter using clear text divided into easily accessible sections and subsections. Tables, figures and photographs are used where appropriate as well as boxed case studies and summary notes. References to important previous studies and results are included but are used sparingly to avoid overloading the text. Suggestions for further reading are also provided. The main target readership is introductory level undergraduate students of physical geography or environmental science, but there will be much of interest to students from other disciplines and it is also hoped that sixth form teachers will be able to use the information that is provided in each volume.

*John Gerrard*

# PREFACE TO THE THIRD EDITION

It is 17 years since the first edition of *Fundamentals of Hydrology* was published – time enough to reflect on what has changed in hydrology during this time. One very positive change is that hydrology is now much more integrated within environmental science. It is common to hear reference to catchment science or water management rather than straight hydrology which shows an interest in more than just the physics of water transfer; people are interested in how water affects their health, their livelihoods and the natural world around them. This textbook set out to bring together the discipline of hydrology with aspects of water quality, ecology and natural resource management so it is pleasing to see this type of integrated thinking reflected in scientific literature, university teaching and public debate. If *Fundamentals of Hydrology* has helped in any small way to bring about that change then that is a very positive outcome.

A second area of significant change has been in instrumentation, particularly the rise of fast and small electronic circuitry. This means that we can measure environmental variables in a less intrusive, better and faster way; often continuously rather than at a single point in time. Two obvious examples of this are acoustic doppler streamflow measurement where we can measure river velocities throughout the total water column and optical water quality sensors where we can measure nitrate concentrations continuously in a river. These types of measurements improve our understanding of hydrological processes in both space and time but can also be important information for understanding ecological and land management processes, which in turn promotes the type of integrated science referred to above.

One of the challenges of improved measurement techniques is the quantity of data produced and how to make sense of it all. Fortunately, there has been a corresponding rise in computing power and ability to store these data 'mountains'. An exciting development for this is the rise of artificial intelligence and data mining techniques using fuzzy logic or similar. These types of techniques offer the possibility of making sense of and seeing patterns within enormous data sets, something that was far beyond the capability of hydrologists 20 years ago.

This third edition of *Fundamentals of Hydrology* has been greatly enhanced by the addition of Nevil Quinn as a co-author: Nevil's skills in flood hydrology, water management and up-to-date university teaching has brought a fresh perspective to the text. I am very grateful for his willingness to take on this task and the many hours spent revising and adding new text. I am grateful to the editors at Routledge, Egle Zigaite and Andrew Mould, who have waited patiently for this third edition to be finished. And finally, I am once again thankful to my wife Chris for putting up with disrupted evenings and weekends while I worked on the text.

*Tim Davie,*
*Christchurch, New Zealand November 2018*

## 1

# HYDROLOGY AS A SCIENCE

## INTRODUCTION

Quite literally, hydrology is 'the science or study of' ('logy' from Latin *logia*) 'water' ('hydro' from Greek *hudor*). However, contemporary hydrology does not study all the properties of water. Modern hydrology is concerned with the distribution of water on the surface of the earth; its movement over and beneath the surface, and through the atmosphere. This wide-ranging definition suggests that all water comes under the remit of a hydrologist, while in reality it is the study of fresh water that is of primary concern. The study of the saline water on earth is carried out in oceanography.

When studying the distribution and movement of water it is inevitable that the role of human interaction with it comes into play. Although human needs for water are not the only motivating force in a desire to understand hydrology, they are probably the strongest. This book attempts to integrate the physical processes of hydrology with an understanding of human interaction with fresh water. The human interaction can take the form of water quantity problems (e.g. over-extraction of **groundwater**) or water quality issues (e.g. disposal of pollutants).

> Water is among the most essential requisites that nature provides to sustain life for plants, animals and humans. The total quantity of fresh water on earth could satisfy all the needs of the human population if it were evenly distributed and accessible.
>
> (Stumm 1986: 201)

Although written around 30 years ago, the views expressed by Stumm are still apt today. The real point of Stumm's statement is that water on earth is not evenly distributed and is not evenly accessible. It is the purpose of hydrology as a pure science to explore these disparities and try to explain them. It is the aim of hydrology as an applied science to take the knowledge of why any disparities exist and try to lessen the impact of them. There is much more to hydrology than just supplying water for human needs (e.g. studying floods as natural hazards; the investigation of lakes and rivers for ecological habitats), but analysis of this quotation gives good grounds for looking at different approaches to the study of hydrology.

The two main pathways to the study of hydrology come from engineering and geography, particularly the earth science side of geography. The earth science approach comes from the study of landforms (**geomorphology**) and is rooted in a history of explaining the processes that lead to water moving around the earth and to try to understand spatial links between the processes. The engineering approach tends to be a little more practically based and looks towards finding solutions to problems posed by water moving (or not moving) around the earth. In reality there are huge areas of overlap between the two and it is often difficult to separate them, particularly when you enter into hydrological research. At an undergraduate level, however, the difference manifests itself through earth science hydrology being more descriptive (understanding processes) and engineering hydrology being more numerate (quantifying flows). Within the broad discipline of hydrology there are also areas of specialisation. For example, some hydrologists focus on groundwater and this specialised area is known as geohydrology or hydrogeology. In recent decades another area of specialisation has emerged; that of ecohydrology or hydroecology. This is the study of hydrology in relation to the natural aquatic environment (e.g. rivers and wetlands) and the important interdependence of water and ecosystems.

The approach taken in this book is more towards the earth science side, a reflection of the authors' training and interests, but it is inevitable that there is considerable crossover. There are parts of the book that describe numerical techniques of fundamental importance to any practising hydrologist from whatever background, and it is hoped that the book can be used by all undergraduate students of hydrology.

Throughout the book there are highlighted case studies to illustrate different points made in the text. The case studies are drawn from research projects or different hydrological events around the world and are aimed at reinforcing the text elsewhere in the same chapter. Where appropriate, there are highlighted worked examples illustrating the use of a particular technique on a real data set.

## IMPORTANCE OF WATER

Water is the most common substance on the surface of the earth, with the oceans covering over 70 per cent of the planet. Water is one of the few substances that can be found in all three states (i.e. gas, liquid and solid) within the earth's climatic range. The very presence of water in all three forms makes it possible for the earth to have a climate that is habitable for life forms: water acts as a *climate ameliorator* through the energy absorbed and released during transformation between the different phases. In addition to lessening climatic extremes the transformation of water between gas, liquid and solid phases is vital for the transfer of energy around the globe: moving energy from the equatorial regions towards the poles. The low viscosity of water makes it an extremely efficient transport agent, whether through international shipping or river and canal navigation. These characteristics can be described as the *physical properties* of water and they are critical for human survival on planet earth.

The *chemical properties* of water are equally important for our everyday existence. Water is one of the best solvents naturally occurring on the planet. This makes water vital for cleanliness: we use it for washing but also for the disposal of pollutants. The solvent properties of water allow the uptake of vital nutrients from the soil and into plants; this then allows the transfer of the nutrients within a plant's structure. The ability of water to dissolve gases such as oxygen allows life to be sustained within bodies of water such as rivers, lakes and oceans.

The capability of water to support life goes beyond bodies of water; the human body is composed of around 60 per cent water. The majority of this water is within cells, but there is a significant proportion (around 34 per cent) that moves around the body carrying dissolved chemicals which are vital for sustaining our lives (Ross and Wilson 1981). Our bodies can store up energy reserves that allow us to survive without food for weeks but not more than days without water.

There are many other ways that water affects our very being. In places such as Norway, parts of the USA and New Zealand, energy generation for domestic and industrial consumption is through hydro-electric schemes, harnessing the combination of water and gravity in a (by and large) sustainable manner. Water plays a large part in the spiritual lives of millions of people. In Christianity, baptism with water is a powerful symbol of cleansing and God offers 'streams of living water' to those who believe (John 7:38). In Islam there is washing with water before entering a mosque for prayer. In Hinduism, bathing in the sacred Ganges provides a religious cleansing. Many other religions give water an important role in sacred texts and rituals.

Water is important because it underpins our very existence: it is part of our physical, material and spiritual lives. The study of water would therefore also seem to underpin our very existence. Before expanding further on the study of hydrology it is first necessary to step back and take a closer look at the properties of water briefly outlined above. Even though water is the most common substance found on the earth's surface, it is also one of the strangest. Many of these strange properties help to contribute to its importance in sustaining life on earth.

## Physical and chemical properties of water

A water molecule consists of two hydrogen atoms bonded to a single oxygen atom (Figure 1.1). The connection between the atoms is through **covalent bonding**: the sharing of an electron from each atom to give a stable pair. This is the strongest type of bonding within molecules and is the reason why water is such a robust compound (i.e. it does not break down into hydrogen and oxygen easily). The robustness of the water molecule means that it stays as a water molecule within our atmosphere because there is not enough energy available to break the covalent bonds and create separate oxygen and hydrogen molecules.

Figure 1.1 shows us that the hydrogen atoms are not arranged around the oxygen atom in a straight line. There is an angle of approximately 105° (i.e. a little larger than a right angle) between the hydrogen atoms. The hydrogen atoms have a positive charge, which means that they repulse each other, but at the same time there are two non-bonding electron pairs on the oxygen atom that also repulse the hydrogen atoms. This leads to the molecular structure shown in Figure 1.1. A water molecule can be described as *bipolar*, which means that there is a positive and negative side to the molecule. This polarity is an important property of water as it leads to the bonding between molecules of water: **hydrogen bonding**. The positive side of the molecule (i.e. the hydrogen side) is attracted to the negative side (i.e. the oxygen atom) of another molecule and a weak hydrogen bond is formed (Figure 1.2). The weakness of this bond means that it can be broken

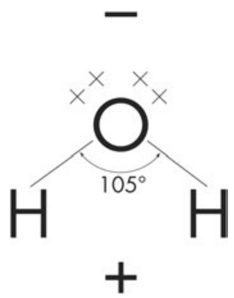


*Figure 1.1* The atomic structure of a water molecule. The spare electron pairs on an oxygen atom are shown as small crosses.

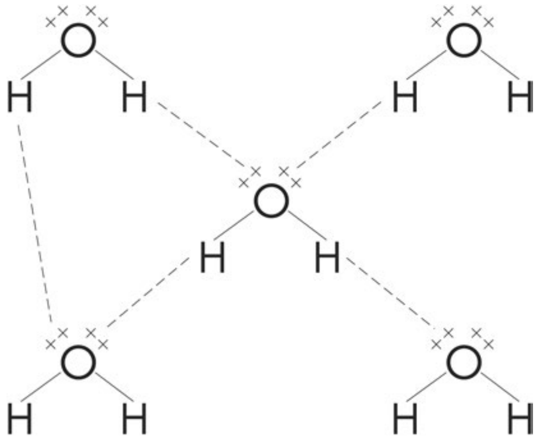


*Figure 1.2* The arrangement of water molecules with hydrogen bonds. The stronger covalent bonds between hydrogen and water atoms are shown as solid lines.

*Source*: Redrawn from McDonald and Kay (1988) and Russell (1976) with the application of some force and the water molecules separate, forming water in a gaseous state (**water vapour**). Although this sounds easy, it actually takes a lot of energy to break the hydrogen bonds between water molecules. This leads to a high specific heat capacity whereby a large amount of energy is absorbed by the water to cause a small rise in energy.

The lack of rigidity in the hydrogen bonds between liquid water molecules gives it two more important properties: a low viscosity and the ability to act as an effective solvent. Low viscosity comes from water molecules not being so tightly bound together that they cannot separate when a force is applied to them. This makes water an extremely efficient transport mechanism. When a ship applies force to the water molecules they move aside to let it pass! The ability to act as an efficient solvent comes through water molecules disassociating from each other and being able to surround charged compounds contained within them. As described earlier, the ability of water to act as an efficient solvent allows us to use it for washing and the disposal of pollutants, and also allows nutrients to pass from the soil to a plant.

In water's solid state (i.e. ice) the hydrogen bonds become rigid and a three-dimensional crystalline structure forms. An unusual property of water is that the solid form has a lower density than the liquid form, something that is rare in other compounds. This property has profound implications for the world we live in as it means that ice floats on water. More importantly for aquatic life, it means that water freezes from the top down rather than the other way around. If water froze from the bottom up, then aquatic flora and fauna would be forced upwards as the water froze and eventually end up stranded on the surface of a pond, river or sea. As it is, the flora and fauna are able to survive underneath the ice in liquid water. The maximum density of water actually occurs at around 4 °C (see Figure 1.3) so that still bodies of water such as lakes and ponds will display thermal stratification, with water close to 4 °C sinking to the bottom.

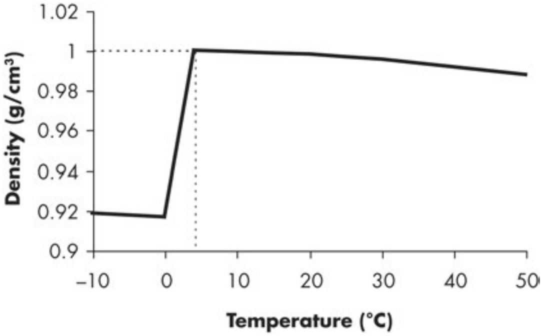


*Figure 1.3* The density of water with temperature. The broken line shows the maximum density of water at 3.98 °C.

Water requires a large amount of energy to heat it up. This can be assessed through the **specific heat capacity**, which is the amount of energy required to raise the temperature of a substance by a single degree. Water has a high specific heat capacity relative to other substances (Table 1.1). It requires 4,200 joules of energy to raise the temperature of 1 kilogram of liquid water (approximately 1 litre) by a single degree. In contrast dry soil has a specific heat capacity of around 1.1 kJ/kg/K (it varies according to mineral make up and organic content) and alcohol 0.7 kJ/kg/K. Heating causes the movement of water molecules and that movement requires the breaking of the hydrogen bonds linking them. The large amount of energy required to break the hydrogen bonds in water gives it such a high specific heat capacity.

We can see evidence of water's high specific heat capacity in bathing waters away from the tropics. It is common for sea temperatures to be much lower than air temperatures in high summer since the water is absorbing all the solar radiation and heating up very slowly. In contrast the water temperature also decreases slowly, leading to the sea often being warmer than the air during autumn and winter. As the water cools down it starts to release the energy that it absorbed as it heated up. Consequently for every drop in temperature of 1 °C a single kilogram of water releases 4.2 kJ of energy

*Table 1.1* Specific heat capacity of various substances

| *Substance* | *Specific heat capacity (kJ/kg/K)* |
|---|---|
| Water | 4.2 |
| Dry soil | 1.1 |
| Ethanol (alcohol) | 0.7 |
| Iron | 0.44 |

into the atmosphere. It is this that makes water a climate ameliorator. During the summer months a water body will absorb large amounts of energy as it slowly warms up; in an area without a water body, that energy would heat the earth much quicker (i.e. dry soil in Table 1.1) and consequently air temperatures would be higher. In the winter the energy is slowly released from the water as it cools down and is available for heating the atmosphere nearby. This is why a maritime climate has cooler summers, but warmer winters, than a continental climate.

The energy required to break hydrogen bonds is also the mechanism by which large amounts of energy are transported away from the hot equatorial regions towards the cooler poles. As water evaporates, the hydrogen bonds between liquid molecules are broken. This requires a large amount of energy. The first law of thermodynamics states that energy cannot be destroyed, only transformed into another form. In this case the energy absorbed by the water particles while breaking the hydrogen bonds is transformed into latent heat that is then released as sensible heat as the water precipitates (i.e. returns to a liquid form). In the meantime the water has often moved considerable distances in weather systems, taking the latent energy with it. It is estimated that water movement accounts for 70 per cent of lateral global energy transport through latent heat transfer (Mauser and Schädlich 1998), also known as **advective energy**.

Water acts as a climate ameliorator in one other way: water vapour is a powerful greenhouse gas. Radiation direct from the sun (short-wave radiation) passes straight through the atmosphere and may be then absorbed by the earth's surface. This energy is normally re-radiated back from the earth's surface in a different form (long-wave radiation). The long-wave radiation is absorbed by the gaseous water molecules and consequently does not escape the atmosphere. This leads to the gradual warming of the earth–atmosphere system as there is an imbalance between the incoming and outgoing radiation. It is the presence of water vapour in our atmosphere (and other gases such as carbon dioxide and methane) that has allowed the planet to be warm enough to support all of the present life forms that exist.

Figure 1.4 shows the phase transitions of water and the name of the corresponding process. While some of these processes have already been mentioned, it is important to be familiar with all of them. One that is particularly relevant for the next chapter is **desublimation** or **deposition**. This is where ice forms directly from water vapour. It is also important to note that at normal atmospheric pressure and at temperatures between 0 °C and 100 °C, liquid water is in a stable state, as is water vapour above temperatures of 100 °C, and ice below 0 °C. However water can also exist in metastable states, and importantly these often occur in the atmosphere. Between temperatures of 0 °C and as low as −40 °C, metastable water can exist in liquid form, known as **supercooled water**. Equally, metastable water vapour can exist alongside stable ice and metastable supercooled water. When supercooled liquid water comes into contact with ice, instantaneous freezing occurs. Note that some meteorologists use sublimation to mean both a phase transformation from solid to gas, and also the reverse process. To avoid confusion we will use the equivalent terms deposition and desublimation to refer to the process of a gas becoming a solid without the intermediate liquid phase.

## The catchment or river basin

In studying hydrology the most common spatial unit of consideration is the **catchment** or

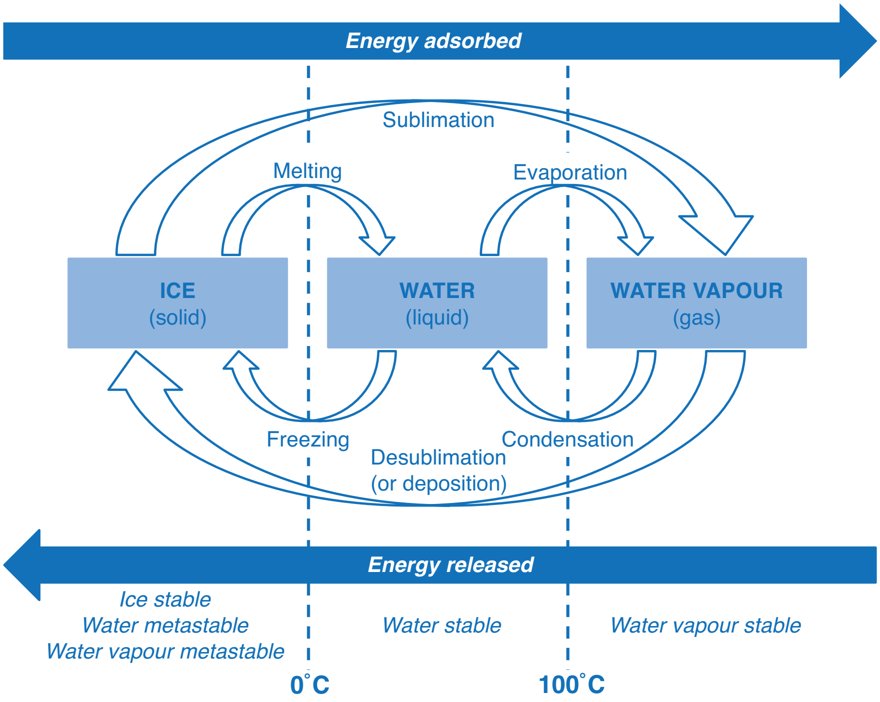


*Figure 1.4* Phase changes of water under normal atmospheric conditions and related terminology.

*Source:* Adapted from Kump et al. (2011)

**river basin**. This can be defined as the area of land from which water flows towards a river and then in that river to the sea. The terminology suggests that the area is analogous to a basin where all water moves towards a central point (i.e. the plug hole of a basin, or in this case, the river mouth). The common denominator of any point in a catchment is that wherever rain falls, it will end up in the same place: where the river meets the sea (unless lost through evaporation). A catchment may range in size from a matter of hectares to millions of square kilometres, and all catchments are, in reality, made up of a set of nested sub-catchments.

A river basin can be defined in terms of its topography through the assumption that all water falling on the surface flows downhill. In this way a catchment boundary (or divide) can be drawn (catchment delineation) (as in Figure 1.5) which defines the actual catchment area for a river basin. In some parts of the world a river basin is also referred to as a **watershed** – this word stems from the fact that at the catchment boundary water is either 'shed' into one basin or an adjacent basin. Strictly speaking therefore 'watershed' refers to the catchment boundary or divide. The assumption that all water flows downhill to the river is not always correct, especially where the underlying geology of a catchment is complicated. It is possible for water to flow as groundwater into another catchment area, creating a problem for the definition of 'catchment area'. This means that the surface water catchment and the groundwater catchment are not necessarily the same (Figure 1.6). These

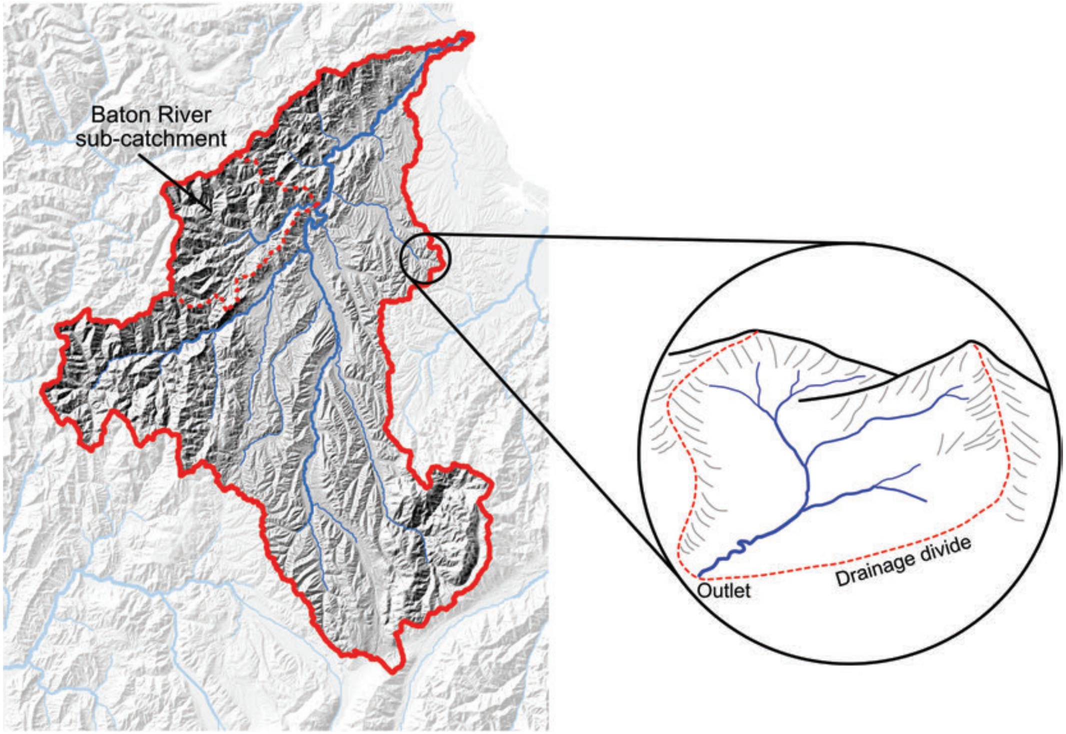


*Figure 1.5* Left: Map of the Motueka catchment/watershed, a 2,180 km$^2$ catchment draining northward at the top of the South Island, New Zealand. Topography is indicated by shading. The Baton river sub-catchment is represented by the dotted outline. Right: A schematic view of a typical small sub-catchment.

*Source*: Digital elevation model based on USGS 2006 Shuttle Radar Topography Mission. Catchment schematic from Charlton (2008)

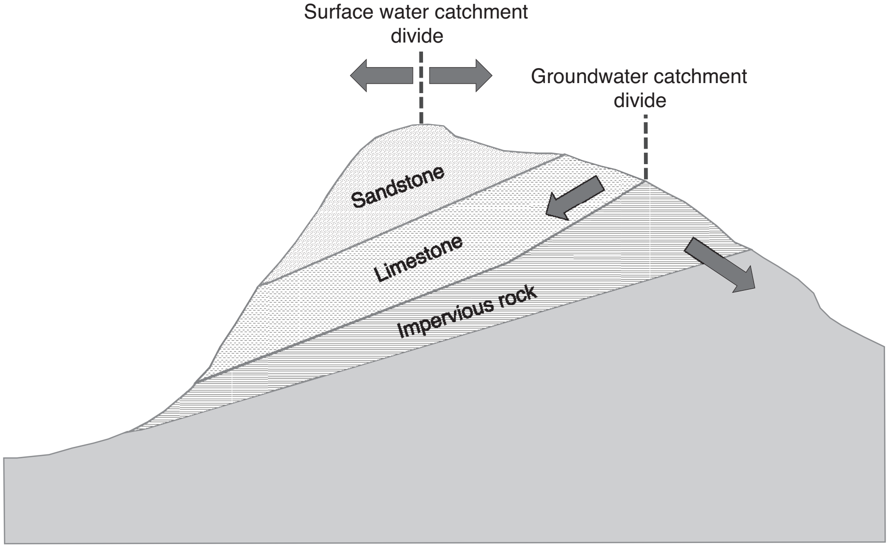


*Figure 1.6* The difference between a surface water divide and a groundwater divide. Arrows represent the direction of surface and groundwater flow.

problems aside, the catchment does provide an important spatial unit for hydrologists to consider how water is moving about and is distributed at a certain time.

## THE HYDROLOGICAL CYCLE

As a starting point for the study of hydrology it is useful to consider the **hydrological cycle**. This is a conceptual model of how water moves around between the earth and atmosphere in different states as a gas, liquid or solid. As with any conceptual model it contains many gross simplifications; these are discussed in this section. There are different scales at which the hydrological cycle can be viewed, but it is helpful to start at the large global scale and then move to the smaller hydrological unit of a river basin or catchment.

### The global hydrological cycle

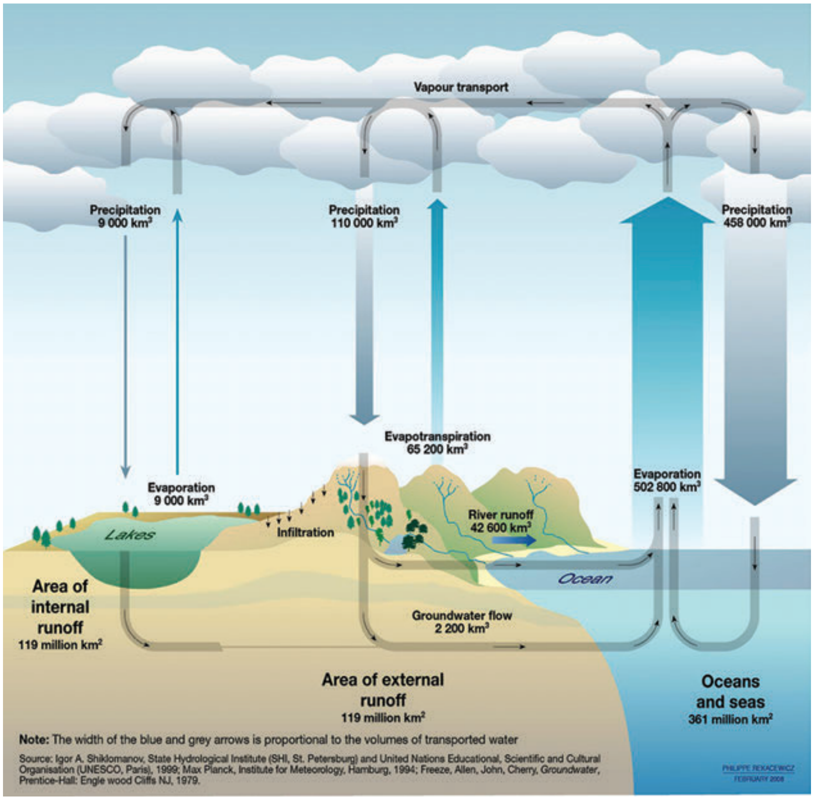
Table 1.2 sets out an estimate for the amount of water held on the earth at a single time. These figures are extremely hard to estimate accurately. Estimates cited in Gleick (1993) show a range in total from 1.36 to 1.45 thousand million (or US billion) cubic kilometres of water. The vast majority of this is contained in the oceans and seas. If you were to count groundwater less than 1km in depth as 'available' and discount snow and ice, then the total percentage of water available for human consumption is around 0.27 per cent. Although this sounds very little it works out at about 146 million litres of water per person per day (assuming a world population of 7 billion); hence the ease with which Stumm (1986) was able to state that there is enough to satisfy all human needs.

Figure 1.7 shows the movement of water around the earth–atmosphere system and is a representation of the global hydrological cycle. The cycle consists of **evaporation** of liquid water into water vapour that is moved around the atmosphere. At some stage the water vapour condenses into a liquid (or solid) again and falls to the surface as **precipitation**. The oceans evaporate more water than they receive as precipitation, while the opposite is true over the continents. The difference between precipitation and evaporation in the terrestrial zone is **runoff**, water moving over or under the surface towards the oceans, which completes the hydrological cycle. As can be seen

*Table 1.2* Estimated volumes of water held at the earth's surface

| | *Volume ($\times 10^3$ km$^3$)* | *Percentage of total* |
|---|---|---|
| Oceans and seas | 1,338,000 | 96.54 |
| Ice caps and glaciers | 24,064 | 1.74 |
| Groundwater | 23,400 | 1.69 |
| Permafrost | 300 | 0.022 |
| Lakes | 176 | 0.013 |
| Soil | 16.5 | 0.001 |
| Atmosphere | 12.9 | 0.0009 |
| Marsh/wetlands | 11.5 | 0.0008 |
| Rivers | 2.12 | 0.00015 |
| Biota | 1.12 | 0.00008 |
| Total | 1,385,984 | 100.00 |

*Source*: Data from Shiklomanov and Sokolov (1983)



**Note:** The width of the blue and grey arrows is proportional to the volumes of transported water

Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, Groundwater, Prentice-Hall: Engle wood Cliffs NJ, 1979.

*Figure 1.7* The global hydrological cycle. The numbers represent estimates on the total amount of water (km$^3$) in each process per annum. The thickness of the arrows denotes the proportional volume.

*Source*: Figure drawn by Philippe Rekacewicz (GRID-Arendal) (based on data from UNEP (2008))

in Figure 1.7, where the width of the arrows is proportional to the volume, the vast majority of evaporation and precipitation occurs over the oceans. Ironically this means that the terrestrial zone, which is of greatest concern to hydrologists, is actually rather insignificant in global terms.

The processes shown in Figure 1.7 (evaporation, precipitation and runoff) are the fundamental processes of concern in hydrology. The figures given in the diagram are global totals, but they vary enormously around the globe. This is illustrated in Figure 1.8 which shows how total precipitation is partitioned towards different hydrological processes in differing amounts depending on climate. In temperate climates (i.e. non-tropical or polar) around one third of precipitation becomes evaporation, one third surface runoff and the final third as groundwater recharge. In arid and semi-arid regions the proportion of evaporation is much greater, at the expense of groundwater recharge.

With the advent of satellite monitoring of the earth's surface in the past 40 years it is now possible to gather information on the global distribution