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HYDROLOGY AS A SCIENCE

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 and 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 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: p201)

Although written over twenty 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 those disparities and try and 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 is looking 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 and engineering hydrology being more numerate.

The approach taken in this book is more towards the earth science side, a reflection of the author's 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 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 (see p. 4) whereby a large amount of energy is absorbed by the water to cause a small rise in energy.

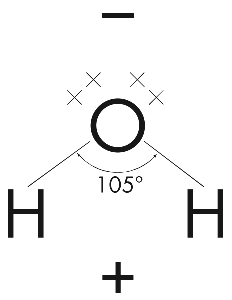

Figure 1.1 The atomic structure of a water molecule. The spare electron pairs on an oxygen atom are shown as small crosses.

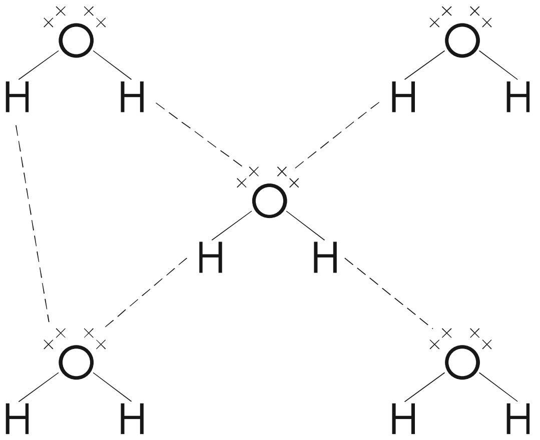

Figure 1.2 The arrangement of water molecules with hydrogen bonds. The stronger covalent bonds between hydrogen and water atoms are shown as solid lines.

Source: Redrawn from McDonald and Kay (1988) and Russell (1976)

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, 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 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.

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.

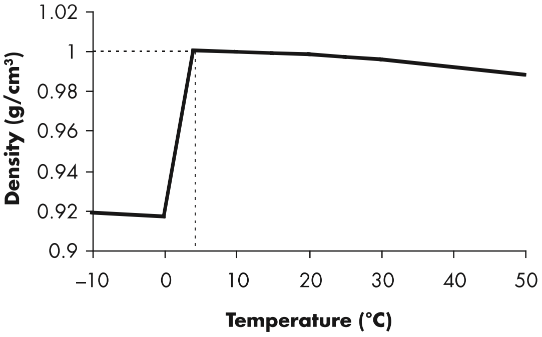

Figure 1.3 The density of water with temperature. The broken line shows the maximum density of water at 3.98°C.

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 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

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

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).

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.

The catchment or river basin

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

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 can be drawn (as in Figures 1.4 and 1.5) which defines the actual catchment area for a river basin. 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'. These 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 that the hydrological cycle can be viewed at, 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.

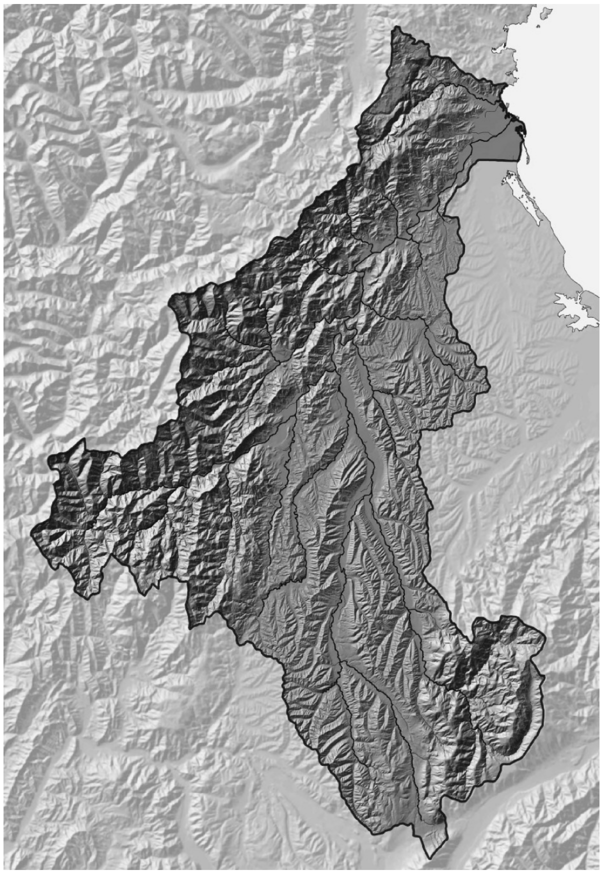

Figure 1.4 (left) Map of the Motueka catchment/watershed, a 2,180 km^2 catchment draining northward at the top of the South Island, New Zealand. Topography is indicated by shading.

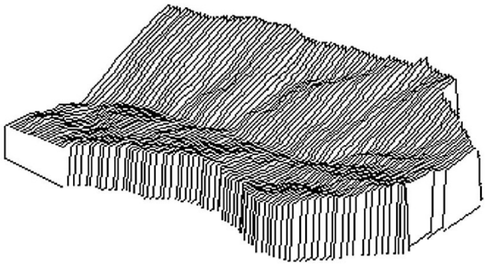

Figure 1.5 A three-dimensional representation of a catchment.

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

	Volume (×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)

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 1 km 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 1.6 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 in Figure 1.6 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 three parts shown in Figure 1.6 (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 1.7 which shows how total precipitation is partitioned towards different hydrological processes

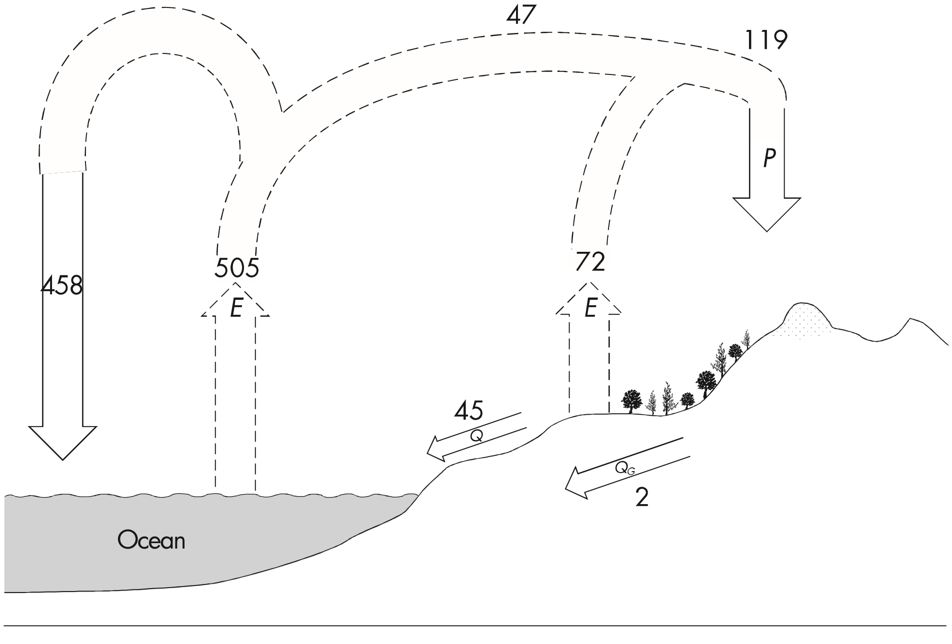

Figure 1.6 The global hydrological cycle. The numbers represent estimates on the total amount of water (thousands of km^3) in each process per annum. E = evaporation; P = precipitation; Q_G = subsurface runoff; Q = surface runoff.

Source: Redrawn from Shiklomanov (1993)

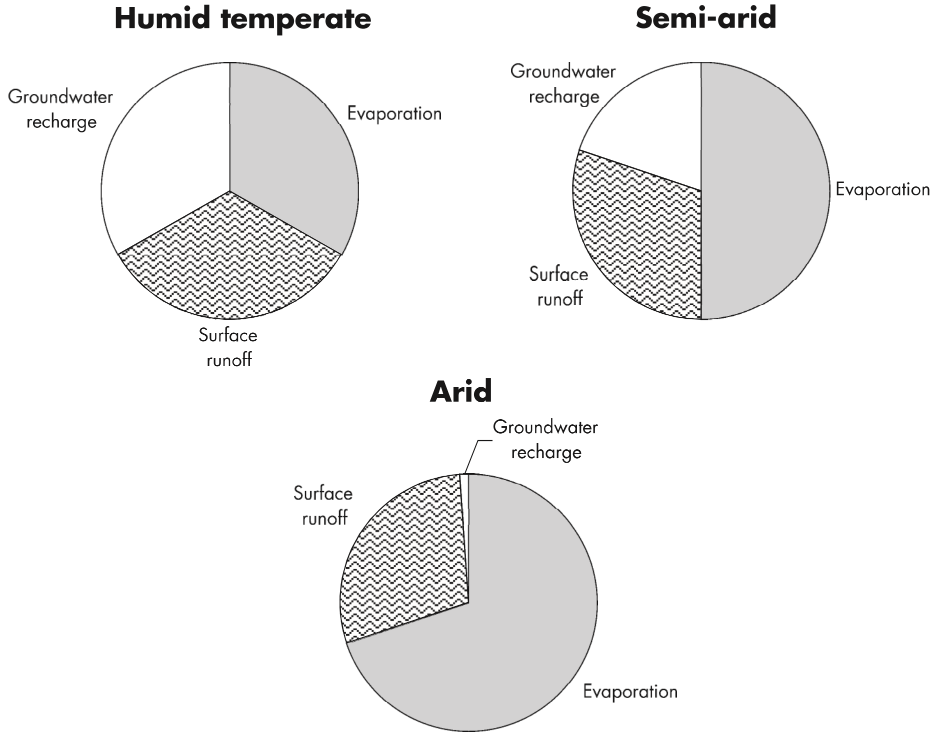

Figure 1.7 Proportion of total precipitation that returns to evaporation, surface runoff or groundwater recharge in three different climate zones.

Source: UNESCO (2006)

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 thirty years it is now possible to gather information on the global distribution of these three processes and hence view how the hydrological cycle varies around the world. In Plates 1 and 2 there are two images of global **rainfall** distribution during 1995, one for January and another for July.

The figure given above of 146 million litres of fresh water per person per year is extremely misleading, as the distribution of available water around the globe varies enormously. The concept of available water considers not only the distribution of rainfall but also population. Table 1.3 gives some indication of those countries that could be considered water rich and water poor in terms of available water. Even this is misleading as a country such as Australia is so large that the high rainfall received in the tropical north-west compensates for the extreme lack of rainfall elsewhere; hence it is considered water rich. The use of rainfall alone is also misleading as it does not consider the importation of water passing across borders, through rivers and groundwater movement.

Table 1.3 gives the amount of available water for various countries, but this takes no account for the amount of water abstracted for actual usage. Figure

1.8 shows the water abstraction per capita for all of the OECD countries. This shows that the USA, Canada and Australia are very high water users, reflecting a very large amount of water used for agricultural and industrial production. The largest water user is the USA with 1,730 m^3 per capita per annum, which is still only 1 per cent of the 146 million litres per capita per annum derived from the Stumm quote. Australia as a high water user has run into enormous difficulties in the years 2005–2007

Table 1.3 Annual renewable water resources per capita (1990 figures) of the seven resource-richest and poorest countries (and other selected countries). Annual renewable water resource is based upon the rainfall within each country; in many cases this is based on estimated figures

Water resource richest countries	*Annual internal renewable water resources per capita (thousand m^3/yr)*	*Water resource poorest countries*	*Annual internal renewable water resources per capita (thousand m^3/yr)*
Iceland	671.9	Bahrain	0.00
Suriname	496.3	Kuwait	0.00
Guyana	231.7	Qatar	0.06
Papua New Guinea	199.7	Malta	0.07
Solomon Islands	149.0	Yemen Arab Republic	0.12
Gabon	140.1	Saudi Arabia	0.16
New Zealand	117.5	United Arab Emirates	0.19
Canada	109.4	Israel	0.37
Australia	20.5	Kenya	0.59
USA	9.9	United Kingdom	2.11

Source: Data from Gleick (1993)

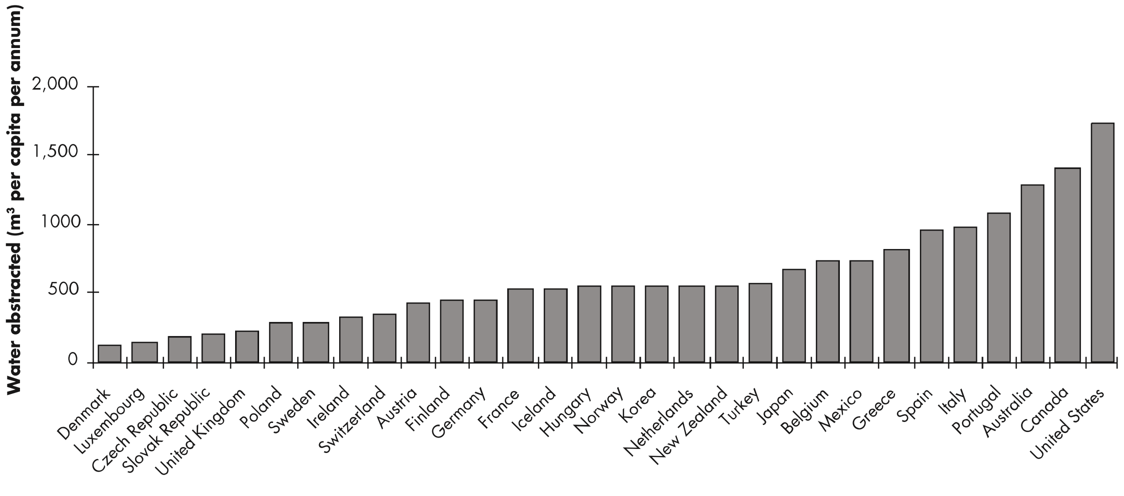

Figure 1.8 Water abstracted per capita for the OECD countries.

Source: OECD Factbook 2005

with severe drought, limiting water availability for domestic and agricultural users. In a situation like this the way that water is allocated (see Chapter 8) literally becomes a matter of life and death, and many economic livelihoods depend on equitable allocation of a scarce water resource.

To try and overcome some of the difficulties in interpreting the data in Figure 1.6 and Table 1.2 hydrologists often work at a scale of more relevance to the physical processes occurring. This is frequently the water basin or catchment scale (Figures 1.4 and 1.5).

The catchment hydrological cycle

At a smaller scale it is possible to view the catchment hydrological cycle as a more in-depth conceptual model of the hydrological processes operating. Figure 1.9 shows an adaptation of the global hydrological cycle to show the processes operating within a catchment. In Figure 1.9 there are still essentially three processes operating (evaporation, precipitation and runoff), but it is possible to subdivide each into different sub-processes. Evaporation is a mixture of open water evaporation (i.e. from rivers and lakes); evaporation from the soil; evaporation from plant surfaces; **interception**; and **transpiration** from plants. Precipitation can be in the form of **snowfall**, hail, rainfall or some mixture of the three (sleet). Interception of precipitation by plants makes the water available for evaporation again before it even reaches the soil surface. The broad term 'runoff' incorporates the movement of liquid water above and below the surface of the earth. The movement of water below the surface necessitates an understanding of infiltration into the soil and how the water moves in the unsaturated zone (**throughflow**) and in the saturated zone (**groundwater flow**). All of these processes and sub-processes are dealt with in detail in later chapters; what is important to realise at this stage is that it is part of one continuous cycle that moves water around the globe and that they may all be operating at different times within a river basin.

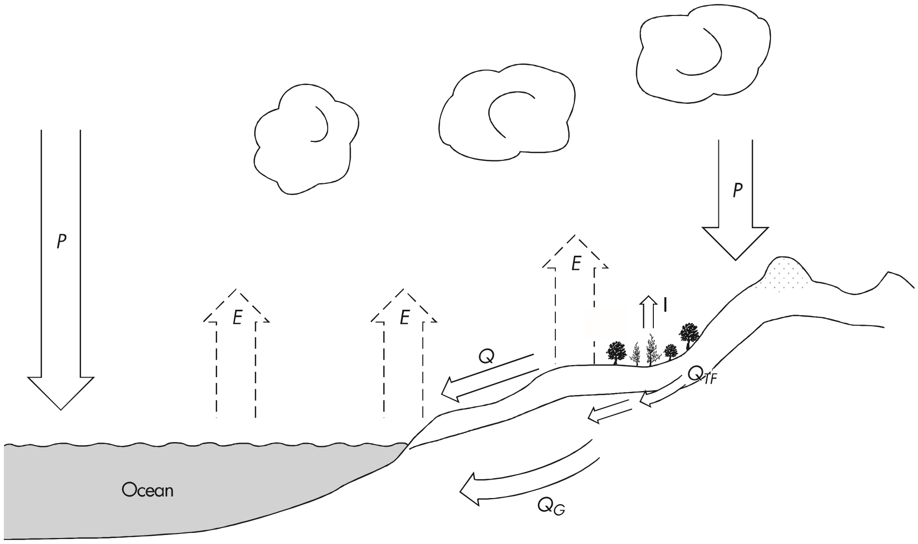

Figure 1.9 Processes in the hydrological cycle operating at the basin or catchment scale. Q = runoff; the subscript G stands for groundwater flow; TF for throughflow; I = interception; E = evaporation; P = precipitation.
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THE WATER BALANCE EQUATION

In the previous section it was stated that the hydrological cycle is a conceptual model representing our understanding of which processes are operating within an overall earth–atmosphere system. It is also possible to represent this in the form of an equation, which is normally termed the **water balance equation**. The water balance equation is a mathematical description of the hydrological processes operating within a given timeframe and incorporates principles of mass and energy continuity. In this way the hydrological cycle is defined as a closed system whereby there is no mass or energy created or lost within it. The mass of concern in this case is water.

There are numerous ways of representing the water balance equation but equation 1.1 shows it in its most fundamental form.

$$P \pm E \pm \Delta S \pm Q = 0 \tag{1.1}$$

where P is precipitation; E is evaporation; ΔS is the change in **storage** and Q is runoff. Runoff is normally given the notation of Q to distinguish it from rainfall which is often given the symbol R and frequently forms the major component of precipitation. The ± terminology in equation 1.1 represents the fact that each term can be either positive or negative depending on which way you view it – for example, precipitation is a gain (positive) to the earth but a loss (negative) to the atmosphere. As most hydrology is concerned with water on or about the earth's surface it is customary to consider the terms as positive when they represent a gain to the earth.

Two of the more common ways of expressing the water balance are shown in equations 1.2 and 1.3

$$P - Q - E - \Delta S = 0 \tag{1.2}$$

$$Q = P - E - \Delta S \tag{1.3}$$

In equations 1.2 and 1.3 the change in storage term can be either positive or negative, as water can be released from storage (negative) or absorbed into storage (positive).

The terms in the water balance equation can be recognised as a series of fluxes and stores. A **flux** is a rate of flow of some quantity (Goudie *et al.*, 1994): in the case of hydrology the quantity is water. The water balance equation assesses the relative flux of water to and from the surface with a storage term also incorporated. A large part of hydrology is involved in measuring or estimating the amount of water involved in this flux transfer and storage of water.

Precipitation in the water balance equation represents the main input of water to a surface (e.g. a catchment). As explained on p. 10, precipitation is a flux of both rainfall and snowfall. Evaporation as a flux includes that from open water bodies (lakes, ponds, rivers), the soil surface and vegetation (including both interception and transpiration from plants). The storage term includes soil moisture, deep groundwater, water in lakes, glaciers, seasonal snow cover. The runoff flux is also explained on p. 10. In essence it is the movement of liquid water above and below the surface of the earth.

The water balance equation is probably the closest that hydrology comes to having a fundamental theory underlying it as a science, and hence almost all hydrological study is based around it. Field catchment studies are frequently trying to measure the different components of the equation in order to assess others. Nearly all hydrological **models** attempt to solve the equation for a given time span – for example, by knowing the amount of rainfall for a given area and estimating the amount of evaporation and change in storage it is possible to calculate the amount of runoff that might be expected.

Despite its position as a fundamental hydrological theory there is still considerable uncertainty about the application of the water balance equation. It is not an uncertainty about the equation itself but rather about how it may be applied. The problem is that all of the processes occur at a spatial and temporal scale (i.e. they operate over a period of time and within a certain area) that may not coincide with the scale at which we make our measurement or estimation. It is this issue of *scale* that makes hydrology appear an imprecise science and it will be discussed further in the remaining chapters of this book.

OUTLINE OF THE BOOK

Fundamentals of Hydrology attempts to bring out the underlying principles in the science of hydrology and place these in a water management context. By and large, water management is concerned with issues of water quantity (floods, droughts, water distribution . . .) and water quality (drinking water, managing aquatic ecosystems . . .). These two management concerns forms the basis for discussion within the book. It starts with the four components of the water balance equation (i.e. precipitation, evaporation, change in storage and runoff) in Chapters 2–5. Precipitation is dealt with in Chapter 2, followed by evaporation, including canopy interception, in Chapter 3. Chapter 4 looks at the storage term from the water balance equation, in particular the role of water stored under the earth's surface as soil water and groundwater and also storage as snow and ice. Chapter 5 is concerned with the runoff processes that lead to water flowing down a channel in a stream or river.

Each of Chapters 2–5 starts with a detailed description of the process under review in the chapter. They then move on to contain a section on how it is possible to measure the process, followed by a section on how it may be estimated. In reality it is not always possible to separate between measurement and estimation as many techniques contain an element of both within them, something that is pointed out in various places within these chapters. Chapters 2–5 finish with a discussion on how the particular process described has relevance to water quantity and quality.

Chapter 6 moves away from a description of process and looks at the methods available to analyse streamflow records. This is one of the main tasks within hydrology and three particular techniques are described: hydrograph analysis (including the unit hydrograph), flow duration curves and frequency analysis. The latter mostly concentrates on **flood frequency analysis**, although there is a short description of how the techniques can be applied to low flows. The chapter also has sections on hydrological modelling and combining ecology and hydrology for instream flow analysis.

Chapter 7 is concerned with water quality in the fresh water environment. This chapter has a description of major water quality parameters, measurement techniques and some strategies used to control water quality.

The final chapter takes an integrated approach to look at different issues of change that affect hydrology. This ranges from water resource management and a changing legislative framework to climate and land use change. These issues are discussed with reference to research studies investigating the different themes. It is intended as a way of capping off the fundamentals of hydrology by looking at real issues facing hydrology in the twenty-first century.

ESSAY QUESTIONS

1. **Discuss the nature of water's physical properties and how important these are in determining the natural climate of the earth.**
2. **Describe how the hydrological cycle varies around the globe.**
3. **How may water-poor countries overcome the lack of water resources within their borders?**

WEBSITES

A warning: although it is often easy to access information via the World Wide Web you should always be careful in utilising it. There is no control on the type of information available or on the data presented. More traditional channels, such as research journals and books, undergo a peer review process where there is some checking of content. This may happen for websites but there is no guarantee that it has happened. You should be wary of treating everything read from the World Wide Web as being correct.

The websites listed here are general sources of hydrological information that may enhance the reading of this book. The majority of addresses are included for the web links provided within their sites. The web addresses were up to date in early 2007 but may change in the future. Hopefully there is enough information provided to enable the use of a search engine to locate updated addresses.

http://www.cig.ensmp.fr/~iahs
International Association of Hydrological Sciences (IAHS): a constituent body of the International Union of Geodesy and Geophysics (IUGG), promoting the interests of hydrology around the world. This has a useful links page.

http://www.cig.ensmp.fr/~hubert/glu/aglo.htm
Part of the IAHS site, this provides a glossary of hydrological terms (in multiple languages).

http://www.worldwater.org
The World's Water, part of the Pacific Institute for Studies in Development, Environment, and Security: this is an organisation that studies water resource issues around the world. There are some useful information sets here.

http://www.ucowr.siu.edu/
Universities Council on Water Resources: 'universities and organizations leading in education, research and public service in water resources'. Disseminates information of interest to the water resources community in the USA.

http://www.ewatercrc.com.au/
Ewater is the successor to the previous Cooperative Research Centre for Catchment Hydrology: an Australian research initiative that focuses on tools and information of use in catchment management.

http://www.wsag.unh.edu/
Water Systems Analysis Group at the University of New Hampshire: undertakes a diverse group of hydrological research projects at different scales and regions. Much useful information and many useful links.

http://www.hydrologynz.org.nz/
Home site for the New Zealand Hydrological Society: has a links page with many hydrological links.

http://www.cof.orst.edu/cof/fe/watershed
Hillslope and Watershed Hydrology Team at Oregon State University: this has many good links and information on the latest research.

http://www.ceh.ac.uk/
Centre for Ecology and Hydrology (formerly Institute of Hydrology) in the UK: a hydrological research institute. There is a very good worldwide links page here.

http://water.usgs.gov
Water Resources Division of the United States Geological Survey (USGS): provides information on groundwater, surface water and water quality throughout the USA.

http://ghrc.msfc.nasa.gov
Global Hydrology Resource Centre: a NASA site with mainly remote sensing data sets of relevance for global hydrology.

http://www.whycos.org/
WHYCOS is a World Meteorological Organization (WMO) programme aiming at improving the basic observation activities, strengthening international cooperation and promoting free exchange of data in the field of hydrology.This website provides information on the System, projects, technical materials, data and links.

http://www.who.int/water_sanitation_health/diseases/en/
This World Health Organization (WHO) section contains fact sheets on over twenty water-related diseases, estimates of the global burden of water-related disease, information on water requirements (quantity, service level) to secure health benefits, and facts and figures on water, sanitation and hygiene links to health.

http://www.unesco.org/water/water_links/
A comprehensive set of hydrological links that can be searched under different themes (e.g. droughts, floods), geographic regions or organisations.