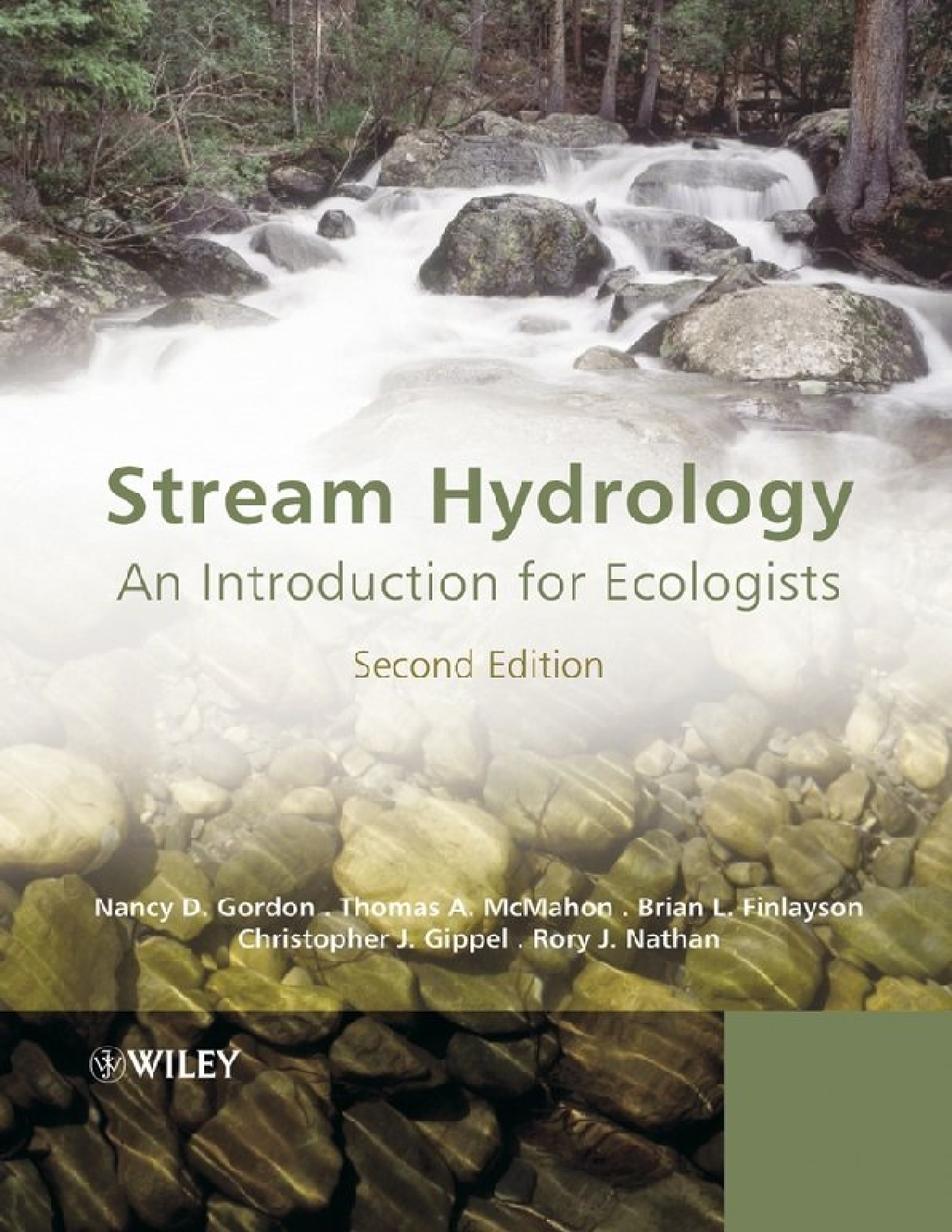

Stream Hydrology

An Introduction for Ecologists

Second Edition

Nancy D. Gordon . Thomas A. McMahon . Brian L. Finlayson
Christopher J. Gippel . Rory J. Nathan

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Preface to the Second Edition

One of the main purposes in writing the first edition of this book in 1992 was to help improve communication between the disciplines of stream ecology and river engineering and to foster a sense of co-operation in these interdisciplinary efforts. We would like to think that we played a part, however small, in assisting the tremendous growth in interdisciplinary and multidisciplinary research and application that followed over the next decade. But this phenomenon was inevitable anyway; academics, policy makers and managers alike had recognised that river management could not take the next step forward unless the various experts got together and problems were assessed and solved from a broad perspective. An engineer, geomorphologist and ecologist will still have a different emphasis when conceptualising a stream, but these days each viewpoint is cognisant of, and is informed by, the others.

This second edition was a long time in its gestation. The field of river research and management has been evolving so rapidly that it was difficult for us to decide when was an appropriate time to update the book. The background information did not present a real problem, as most of it is grounded in long established principles of hydrology and fluid mechanics. However, the real growth area was in the application of science to stream management; the trial and error approach is no longer acceptable. We feel that now is a good time to take stock of these developments. Many countries have implemented new river laws that require managers to at least maintain the current levels of stream health and be highly accountable for their actions. The ecosystem concept, which originated in ecology as a research paradigm, has now been transferred to the realm of public policy; physico-chemical characteristics are still important, but we now speak of ‘‘stream health’’ and measure it in terms of water quality, habitat availability and suitability, energy sources, hydrology, and the biota themselves. Introduction of the European Union Water Framework Directive in December 2000 has already led to widespread changes in assessment of stream health in Europe. Stream classification is now a routine first step that simplifies the inherent complexity of stream systems, helping to facilitate many aspects of the management process. Research has clearly established the impacts of flow regulation, and the last decade has seen considerable growth in research and assessment of environmental flow needs. River rehabilitation is now one of the central themes of the river management industry. One of our objectives in writing this second edition is to bring some methodological order to these developments. Another objective is to critically evaluate the level of success and failure in efforts to rehabilitate streams. This could not have been done in the first edition, because so few examples existed at that time.

In this second edition we maintain an emphasis on the physical environment. Information has been drawn from the fields of geomorphology, hydrology and fluid mechanics, with examples given to highlight the information of biological relevance. Chapters 1–8, which include tools for studying and describing streams, have been updated by the original authors. Chapter 9, which reviews river management applications, has been totally re-written by Dr. Chris Gippel of Fluvial Systems Pty Ltd. In this final chapter, we could not avoid venturing a little further into the biological realm, and we also drew on a much wider range of source material. Readers expecting mathematical derivations will still be disappointed; we concentrate on presenting principles and demonstrating their practical use.

The software package, AQUAPAK (readers of the first edition will be familiar with the original version) has been completely updated by the original author Dr Rory Nathan of Sinclair Knight Merz Pty Ltd. AQUAPAK can be downloaded at http://www.skmconsulting.com/aquapak and runs in Windows. AQUAPAK has been tailor made for the readers of this book and assumes no prior knowledge on the part of the user other than basic computer keyboard skills. More advanced users may wish to investigate the Catchment Modelling Toolkit available on-line from the Cooperative Research Centre for Catchment Hydrology at http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit.

It is clear now that many mistakes have been made in stream management in the past, leading to what we now call stream degradation. This is a retrospective view, because at the time, river managers were acting under the impression that their work would improve the value of the river from the perspective of the prevailing dominant social view. Other failed works were simply ill-informed from the technical perspective. Streams are now managed for a wider range of values, and advances made in stream management technology certainly hold the promise of ecologically healthier and economically more valuable streams for the future. But we have to remember that stream management is far from simple, and an ill-informed approach, regardless of the best intentions, can fail to produce the expected outcomes. So, as well as learning more about river processes, developing methods for rehabilitation and playing a leading role in implementing science-based management, river professionals have a responsibility to provide honest evaluations of the relative success of works. New knowledge so generated can then be used to improve the next generation of river management. At one extreme some may still hold the view that fundamental science does not have much of a role to play in the practical domain of the on-ground river manager, while at the other extreme, some researchers might still be content to explore rivers with little thought about the implications of how the new knowledge might assist practical management or policy development. We hope that this book provides a resource and inspiration to fellow river management professionals, academics and students whose outlook and passion lies some where between, or who are working to bridge these perspectives.

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The authors would like to express appreciation to a number of individuals for their contributions during the evolution of this text. Mr. Andrew Douch created many of the original drawings and diagrams for Chapters 4–6 in the first edition. The diagrams in this edition were re-drawn or newly prepared by Chandra Jayasuriya and Fatima Basic of the School of Anthropology, Geography and Environmental Studies, the University of Melbourne. We are grateful to Dr Michael Keough of the Department of Zoology, University of Melbourne, for producing the realistic examples of Section 2.5. Many individuals, listed in the first edition, provided general guidance and reviews of draft materials that helped focus the scope of the book and greatly added to its accuracy and applicability. Their assistance is again acknowledged. Several reviewers provided suggestions for improvement which added to the quality of this second edition.

We are very appreciative of the professionalism and helpfulness of the people at John Wiley & Sons, especially

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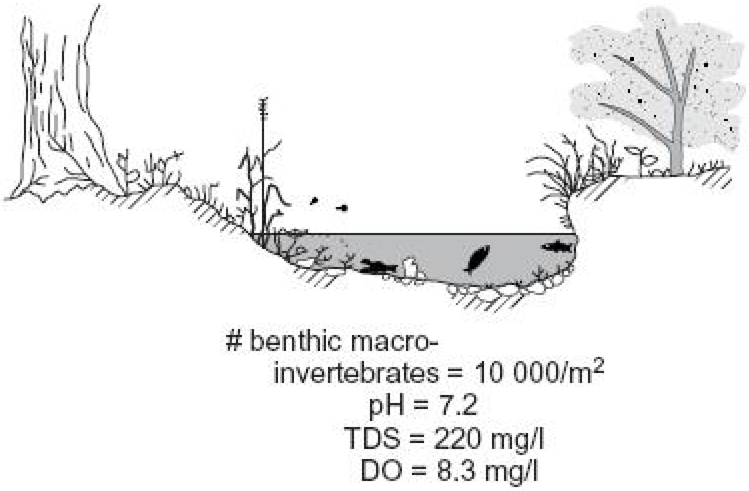
Preface to the First Edition

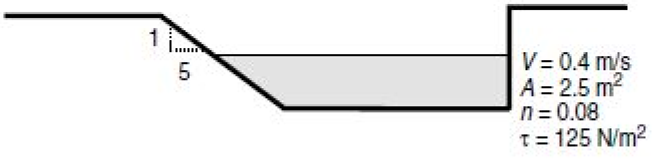
In interdisciplinary applications of stream hydrology, biologists and engineers interact in the solution of a number of problems such as the rehabilitation of streams, the design of operating procedures and fishways for dams, the classification of streams for environmental values and the simulation of field hydraulic characteristics in laboratory flumes to study flow patterns around obstacles and organisms. One of the main purposes in writing this book was to help improve communication between the two disciplines and foster a sense of co-operation in these interdisciplinary efforts.

On the surface, the definitions of ecology and hydrology sound very similar: *ecology* is the study of the interrelationships between organisms and their environment and with each other, and *hydrology* is the study of the interrelationships and interactions between water and its environment in the hydrological cycle. In general, ecology is a more descriptive and experimental science and hydrology is more predictive and analytical. This fundamental difference influences the way streams are studied and perceived in the two disciplines.

For example, a diagram of an ecologist’s view of a stream might appear as follows:



Here, the focus is on the aquatic biota, their interrelations, and the physical and chemical factors which affect them. An engineering hydrologist, on the other hand, might ‘view’ the same stream much differently, perhaps more like this:



In this image, the physical dimensions of the stream have been simplified into a few numbers from which estimates can be made of how the stream will respond under different flow conditions.

Neither view is superior to the other; each represents only a fraction of ‘all there is to know’ about the stream. Interdisciplinary interaction offers a way of merging the information contained in the different views into a more complete picture. It is often at the interface between disciplines, in fact, that new ideas are generated and progress is made. Perhaps like a stereo pair, new ‘dimensions’ will be revealed when the images are successfully superimposed.

The emphasis of this text is on the physical environment. Information has been drawn from the fields of geomorphology, hydrology and fluid mechanics, with examples given to highlight the information of biological relevance. Mathematical derivations have been omitted; instead, the intent was to provide an intuitive understanding of the principles, demonstrate their practical use and leave the mathematics to a computer. A software package, AQUAPAK, has been provided for this purpose. Omissions and simplifications were necessary in conveying the wide range of subject matter. We can only resort to the blanket statement that everything is more complicated than our description of it, and that ours is merely another ‘view’ of streams.

A practical approach has been taken, with the chapter on field techniques forming a central part of the text. In other chapters, examples have been given so that the principles can be applied more readily. Field studies in the Acheron River Basin, located approximately 100 km to the east of Melbourne, provided information for examples throughout the book. We did this to maintain continuity, as well as to illustrate how we went about ‘getting to know’ this river system.

The process of getting to know a stream is not unlike that of a doctor learning about a patient and his or her health. A conscientious doctor will look beyond the charts, images and the results of various tests to obtain a sense of what causes the patient’s health to be what it is. In the same manner, hydrological data, aerial photographs, channel surveys and water quality analyses only measure ‘symptoms’ of a stream’s condition, and, as with human health, the underlying causes are complex and nebulous.

Just as patients are more than the sum of their connective tissues and blood vessels, streams, too, should be viewed ‘holistically’ as a continuum from source to sea and as systems which interact with the surrounding environment. This book presents methods for ‘diagnosing’ the physical condition of streams. Criteria for establishing what constitutes physical ‘health’ are yet to be developed. As Leopold (1960) advocated over 30 years ago, benchmark stations free from grazing and other human influences are needed in order to evaluate the effects of humans on ecologic and geologic change. Interdisciplinary studies are essential for establishing these baseline conditions, for determining the sensitivity of a given stream to ‘stress’ and for developing appropriate rehabilitation procedures to ‘cure’ those streams which are found to be in poor condition.

1

Introducing the Medium

1.1 Water as a Fluid

Water is a widespread, life-sustaining substance, comprising some 50–90% of living materials and covering nearly three-fourths of the Earth's surface. Of the Earth's total moisture, however, about 97% is contained in the oceans and less than 0.0002% flows through its rivers and streams. Water is recycled globally, with the relative proportions of ice, water vapour, fresh water and salt water changing as the earth warms and cools. Scientists formerly believed that the total amount of water on Earth was essentially constant, but new evidence points to a small influx of water from 'snowball' comets (Pielou, 1998).

Water is a substance with many unique chemical and physical properties. Unlike most substances that contract when frozen, water expands, allowing ice to float on the surfaces of lakes and streams. It is found as a liquid at temperatures common to most places on Earth. With its great heat capacity it can absorb or lose a large amount of energy before showing a change in temperature. As a universal solvent, it dissolves gases, nutrients and minerals. Its internal cohesion gives rise to surface tension, which allows water striders to traverse a pool's surface or even run upstream. Because of its physical properties, a quite different set of environmental conditions is presented to amoebae and fish that both live in the same waters.

Depending on the temperature, water can exist as either a liquid, a gas (water vapour) or a solid (ice). Combinations such as steam-air mixtures or water with entrained air fall into a specialized category called *two-phase flows*.

The general term *fluid* describes both gases and liquids, examples being oxygen, motor oil, liquid glass and mercury. The differences between fluids and solids are not always obvious. Fluids flow readily under the slightest of forces; they do not have a definite shape and vessels are required to contain them. *Solids* are substances that are considered to have both a definite volume and a definite shape. Thus, the line is drawn between molasses as a fluid and gelatin as a solid.

Liquids are distinguished from gases by their cohesiveness. Whether sitting in a laboratory beaker or in a frog pond, a liquid will have a definite volume. It will also have a free surface, which is horizontal when the fluid is at rest. A *gas,* in contrast, does not have a definite volume, and will expand to fill a container enclosing it.

The next section will introduce some basic principles of physics and the system of units used in the text. These concepts are applied to the description of physical properties of water in Section 1.3.

1.2 The Physics of Fluids

The properties and motion of a fluid, such as water, are measured in terms of four basic quantities: mass, length, time and temperature. The magnitudes of these quantities (e.g. how hot or how large) are expressed in *units.* In the International System of Units (SI), the *fundamental* or *base units* are given as

- kilogram (kg)—mass,
- metre (m)—length,

- second (s)—time,
- Kelvin (K)—temperature.

In studies of aquatic systems, absolute temperatures are not normally of interest, and for the purposes of this text, temperature will be expressed in °C (Celsius), where 273.15 K = 0 °C, and a change of 1 °C is the same as a change of 1 K.

The metre was originally proposed as 10^{-7} of the length of the meridian through Paris (Blackman, 1969). It is now defined in terms of the wavelength of a specific type of orange light. The unit of time, the second, is defined by an atomic standard based on caesium. The unit of mass was originally based on the mass of a certain volume of water at prescribed conditions. Thus, conveniently, a litre (0.001 m^3) of water at 4 °C has a mass of about 1 kg.

Whereas these base units are all defined in reference to some standard, there are other quantities, such as velocity, for which standards are impractical. These quantities have units that are defined in terms of the base units and are thus called *derived units.* Some of the quantities associated with the area of physics known as ‘mechanics’, which are relevant to the study of water, will be discussed. A summary of both fundamental and derived units, their dimensions and associated symbols, is given in Table 1.1. For tables of conversion factors and other information relevant to water resource studies, Van Haveren’s (1986) handbook is a highly useful reference.

Velocity

Motion is defined as a change of position. *Speed* refers to the rate at which the position changes with time, i.e. if a raft floats 500 m downstream in 5.5 min, then its average speed is about 1.5 m/s. Technically, *velocity* refers to the speed in a given direction; however, in ordinary speech, no distinction is usually made between velocity and speed.

Discharge or Streamflow

Discharge, or *streamflow*, is the rate at which a volume of water flows past a point over some unit of time. In the SI system it is expressed in metres cubed per second (m^3/s). For example, if a small spring filled a 0.01 m^3 bucket in 2 s, its discharge would be 0.005 m^3/s. Discharge is normally symbolized by Q.

Acceleration

Acceleration is the rate at which velocity changes with time. An object dropped off a cliff on Earth will accelerate at 9.807 m/s^2 (this *gravitational acceleration* (g) varies slightly with position on the Earth’s surface). The distance h covered by a dropped object (starting at zero velocity) is

(1.1) $h = \frac{1}{2}gt^2$

where t is the time in seconds from when it was dropped and h is in metres.

Force

Force is described in terms of its effects. It may cause an object to change its direction of motion, to stop or start, to rise or fall. By Newton’s second law of motion, force is proportional to mass multiplied by acceleration. In the SI system, the unit of force is the *Newton* (N), defined as the force necessary to accelerate 1 kg at 1 m/s^2:

Table 1.1. *Common quantities used in the description of fluids. Adapted from Vogel, Steven; Life in Moving Fluids. © 1981 by Willard Grant Press, 1994 revised Princeton*

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$$\text{Force (N)} = \text{Mass (kg)} \times \text{acceleration (m/s}^2\text{)} \quad (1.2)$$

A very small ‘Newton’s’ apple with a mass of 0.102 kg experiences a gravitational force on Earth of about 1 N.

The term ‘weight’ does not appear in the SI system, and can create confusion particularly when converting from the Imperial to the SI system. *Mass* is an expression of the amount of matter in something, whether a brick, a balloon or a bucket of water. *Weight* is a gravitational force. If Newton’s apple were taken to the moon, it would still have a mass of 0.102 kg, but its weight (the force due to gravity) would be considerably reduced. On Earth, if an American buys 2.2 pounds (lb) of apples at the supermarket to make a pie and an Australian buys 1 kg of apples at the greengrocer to make apple slices, they will both get the same amount of produce. In this case, the distinction between mass and weight does not matter. However, to a researcher studying the behaviour of fluids, the distinction is essential!

Pressure

The *pressure* at any point is the force per unit area acting upon the point. For example, a human of 70 kg standing on the top of an empty aluminium can with a surface area of 0.002 m^2 would exert a pressure of

$$\left(\frac{70 \times 9.807}{0.002}\right) \approx 343\,000\,\text{N/m}^2 \text{ or } 343 \text{ kilopascals (kPa)}$$

–probably sufficient to crush it.

Shear Stress and Shear Force

Shear stress, like pressure, is force per unit area. The difference is in the direction in which the force is applied. In pressure, the force acts *perpendicular* to a surface, ⊥ , whereas a *shear force* acts *parallel* to it, ∥. For example, a glob of liquid soap rubbed between the hands experiences shearing forces. Shear stress is the shearing force divided by the area over which it acts. For the soap, the shearing force acts over the surface area where the soap contacts the hand. Shear stress, symbolized by τ (tau), has the same unit as pressure, N/m^2.

Energy and Work

Energy and work have the same units. *Work* is a quantity described by the application of a force over some distance, measured in the direction of the force:

(1.3) $\text{Work (N m or J)} = \text{Force (N)} \times \text{distance (m)}$

For example, if a force of 500 N is required to push a waterlogged log 10 m across a pond, then the amount of work done is 5000 N m or 5 kilojoules (kJ).

Energy is the capacity for doing work. Thus, the quantity of work that something (or someone) can do is a measure of its energy; e.g. it would take about 700 kJ for a person of average ability to swim 1 km. Energy is usually symbolized by Ω (omega).

Power

Power is the amount of work done per unit time:

(1.4) $\text{Power (J/s or Watts)} = \text{Work (J)}/\text{time (s)}$

Power is usually symbolized by ω (lower case omega). For a flow of water, Q, falling over a height, h, the relevant formula for calculating power is

(1.5) $\omega = \rho g Q h$

where ω has units of Watts, Q has units of m^3/s, h is in metres, ρ (rho) is the density of water (kg/m^3) and g is the acceleration due to gravity (m/s^2). As an approximation, this can be simplified to

(1.6) $\omega = 10Qh$

with ω in kilowatts. Thus, if a waterfall of 10 m height is flowing at 1.0 m^3/s, the power of the falling water is 100 kW. If the flow were diverted into a small hydroelectric plant rather than over the waterfall, much of this water power could be converted to electrical power. Because of losses associated with the turbine, electrical generator and diversion works, efficiencies of 70% are common. In this example, then, approximately 70 kW of electricity could be produced.

1.3 Physical Properties of Water

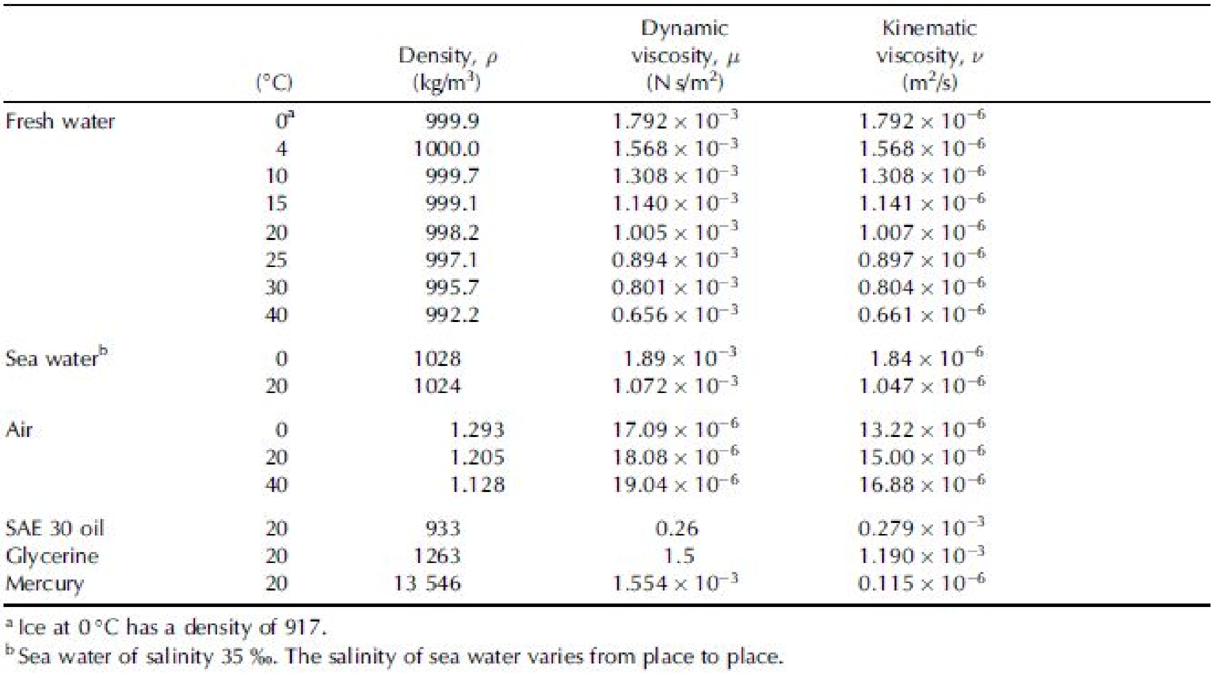
1.3.1 Density and Related Measures

Density

Because the formlessness of water makes mass an awkward quantity, *density,* or mass per unit volume, is typically used instead. Density is normally symbolized by ρ and in the SI system it is expressed in kilograms per cubic metre (kg/m^3).

***Table 1.2**. Values of some fluid properties at atmospheric pressure. Adapted from Douglas et al. (1983) and Vogel*

(1981), by permission of Longman Group, UK, and Princeton University Press, respectively



	(°C)	Density, ρ (kg/m^3)	Dynamic viscosity, μ (N s/m^2)	Kinematic viscosity, ν (m^2/s)
Fresh water	0[a]	999.9	1.792×10^{-3}	1.792×10^{-6}
	4	1000.0	1.568×10^{-3}	1.568×10^{-6}
	10	999.7	1.308×10^{-3}	1.308×10^{-6}
	15	999.1	1.140×10^{-3}	1.141×10^{-6}
	20	998.2	1.005×10^{-3}	1.007×10^{-6}
	25	997.1	0.894×10^{-3}	0.897×10^{-6}
	30	995.7	0.801×10^{-3}	0.804×10^{-6}
	40	992.2	0.656×10^{-3}	0.661×10^{-6}
Sea water[b]	0	1028	1.89×10^{-3}	1.84×10^{-6}
	20	1024	1.072×10^{-3}	1.047×10^{-6}
Air	0	1.293	17.09×10^{-6}	13.22×10^{-6}
	20	1.205	18.08×10^{-6}	15.00×10^{-6}
	40	1.128	19.04×10^{-6}	16.88×10^{-6}
SAE 30 oil	20	933	0.26	0.279×10^{-3}
Glycerine	20	1263	1.5	1.190×10^{-3}
Mercury	20	13 546	1.554×10^{-3}	0.115×10^{-6}

[a] Ice at 0 °C has a density of 917.

[b] Sea water of salinity 35 ‰. The salinity of sea water varies from place to place.

Pressure can be assumed to have an insignificant effect on the density of water for most hydrological applications. However, water density does change with temperature, decreasing as the temperature increases above 4 °C (i.e. tepid water floats on top of colder water). Water density reaches a maximum at 4 °C under normal atmospheric pressure. As the temperature decreases below 4 °C, water becomes less dense, and upon freezing, it expands (ice floats). The densities of selected fluids at different temperatures are listed in Table 1.2.

Materials dissolved or suspended in water, such as salt or sediment or air, will also affect its density. Thus, fresh water will float above salt water in estuarine environments or where saline groundwater enters a stream. Density is reduced in the frothy whitewater of rapids, under waterfalls or in other areas where large quantities of air are entrained in the water. Swimmers have more trouble staying afloat or propelling themselves in these regions; hence, fish tend to ‘jump’ towards their upstream destinations from less-aerated areas (Hynes, 1970).

Specific Weight

Specific weight is a non-SI measure, but is commonly used in practice in the Imperial system in place of density. Usually symbolized by γ (gamma), specific weight is equal to the product of density and gravitational acceleration, ρg. Thus, in the Imperial system, where the specific weight of water (at 4 °C) is 62.4 lb/ft^3, one can calculate the weight of water in a 10 ft^3 aquarium as 62:4 × 10 = 640 lb. This measure will not be used in this text, and is included here only because it appears so often in the literature.

Relative Density

Relative density is usually defined as the ratio of the density of a given substance to that of water at 4 °C. It is thus a dimensionless quantity (it has no units). For example, the relative density of quartz is about 2.68. Relative density is equivalent to *specific gravity,* used in the Imperial system, where specific gravity is defined as the ratio of the specific weight of a substance to that of water.

Example 1.1

Calculate (a) the mass of a 5 L volume of 15 °C fresh water and (b) the gravitational force (weight) it experiences on Earth:

(a) $(5\,\mathrm{L})\left(\frac{.001\,\mathrm{m}^3}{\mathrm{L}}\right)\left(999.1\,\frac{\mathrm{kg}}{\mathrm{m}^3}\right) = 5.0\,\mathrm{kg}$

(b) $5.0\,\mathrm{kg}\left(9.807\,\frac{\mathrm{m}}{\mathrm{s}^2}\right) = 49.0\,\frac{\mathrm{kg\,m}}{\mathrm{s}^2} = 49.0\,\mathrm{N}$

1.3.2 Viscosity and the ‘No-slip Condition’

Viscosity is a property that is intuitively associated with motor oil and the relative rates with which honey and water pour out of a jar. It is related to how rapidly a fluid can be ‘deformed’. When a hand-cranked ice cream maker is empty the handle can be turned relatively easily. If it is then filled with water, the amount of effort increases, and if the water is replaced with molasses, the handle becomes extremely difficult to turn. Viscosity, or more precisely, *dynamic* or *absolute viscosity,* is a measure of this increasing resistance to turning. It has units of Newton seconds per square metre (N s/m^2) and is symbolized by μ (mu). Of interest to aquatic organisms and aquatic researchers is the fact that there is almost no liquid with viscosity lower than that of water (Purcell, 1977).

The dynamic viscosity of water is strongly temperature dependent. Colder water is more ‘syrupy’ than warmer water. For this reason, it takes less effort for a water boatman to row across a tepid backyard pond in summer than the equivalent distance in a frigid high-country lake. It also takes more work for wind to produce waves on a water surface when the water is colder. Dynamic viscosity of fresh water can be calculated directly from temperature using the Poiseulle relationship, given as follows (Stelczer, 1987):

$$\mu = \frac{0.0018}{(1 + 0.0337T + 0.000221T^2)} \qquad (1.7)$$

Eq. (1.7) will give slightly different values than those listed in Table 1.2 for fresh water. It should be noted that salt water has a higher dynamic viscosity than fresh water at the same temperature. Vogel (1981) describes instruments for measuring the viscosity of fluids for which published values are not available.

The influence of viscosity is perhaps most significant in the region where fluids come into contact with solids. It is here that fluids experience the equivalent of friction, which develops entirely within the fluid. When a solid slides across another solid, like shoes across a carpet, friction occurs at the interface between the two solids. When a fluid encounters a solid, however, the fluid sticks to it. There is no movement at the interface. According to this *no-slip condition*, at the point where a viscous fluid contacts a solid surface like a cobble on a streambed or a scale on a fish, its velocity is the same as that of the solid.

Thus, when water flows by a stationary solid object, the velocity of the water is zero where it contacts the solid surface, increasing to some maximum value in the 'free stream'—the region 'free' of the influence of the solid boundary.

Kinematic viscosity, symbolized by ν (nu), is the ratio of dynamic viscosity to density:

$$\text{Kinematic viscosity } (\nu) = \frac{\text{Dynamic viscosity } (\mu)}{\text{Density } (\rho)} \quad (1.8)$$

where ν has units of m^2/s. This ratio shows up frequently in important measures such as the Reynolds number, and is another way of describing how easily fluids flow. The quantity was introduced by engineers to simplify the expression of viscosity (kinematic viscosity has dimensions only of length and time).

From Table 1.2 it can be seen that the kinematic viscosities of air and water are much more similar than their relative dynamic viscosities. The similarities in the behaviour of air and water make it convenient to model air currents, chimney plumes or aircraft in water tanks (after applying appropriate scaling factors).