Modern Hydrology and Sustainable Water Development

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Author Biography

After graduating in geophysics from the Indian Institute of Technology (IIT), Kharagpur, Dr. S.K. Gupta did his PhD from IIT, Bombay in 1974. He is a recipient of the Vikaram Sarabhai National Award in Hydrology and Atmospheric Sciences. Dr. Gupta nucleated the Isotope Hydrology group at the Physical Research Laboratory, Ahmedabad and carried out research for more than past 3 decades. Presently, he is the Principal Coordinator of the National Programme for Isotopic Fingerprinting of Waters of India. Dr. Gupta has more than 150 publications in internationally refereed research journals and several books to his credit. Dr. Gupta has also been a Fulbright Fellow at the University of Hawaii at Manoa and an Alexander von Humboldt Fellow at the University of Heidelberg and a Visiting Fellow at the University of Canberra. He is also a Fellow of the National Academy of Sciences, India.
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A John Wiley & Sons, Ltd., Publication
DEDICATION

to

Prof. D. Lal, FRS

His life and work continue to inspire
my academic endeavours.
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Over the past 50 years the population of the world has increased from 3 billion to 6.5 billion and it is likely to rise by another 2 billion by 2025 and by another 3 billion by 2050. Following the current trends it is certain that the increasing population will mean a greater need for food. More people will dwell in cities and will strive for a higher standard of living. This will imply rapid urbanization, accelerating land-use change, depleting groundwater resources, increasing pollution of surface streams, rivers, and groundwater, and decaying infrastructure. To produce more food, there will be greater pressure on agriculture, which will call for more irrigation. There will be increasing demands for energy, which will also require more water. Thus, the demand for water in both rural and urban areas will rise and outpace the growth in population.

To make matters worse, there is the spectre of climate change. During the last one hundred years, the temperature has arisen by nearly 0.6°C, and it is expected to rise by another 2°C during the next 100 years. This would translate into intensification of the hydrologic cycle, rising sea levels, more variable patterns of rainfall (more intense, more extreme), more changes in runoff (more frequently occurring floods and droughts), shorter snowfall seasons, earlier start of spring snowmelt seasons, melting of glaciers, increasing evaporation, deterioration in water quality, changes to ecosystems, migration of species, changes in plant growth, reaction of trees to downpours, drying up of biomass during droughts, and quicker growing and subsequent wilting of crops. In other words, the entire ecosystem will undergo a significant change at local, regional, and global scales. One can only conjecture on the long-term consequences of such changes.

The impact of climate change on water resources management would entail serious ramifications. Larger floods would overwhelm existing control structures; reservoirs would not receive enough water to store for the use of people and agriculture during droughts; global warming would melt glaciers and cause snow to fall as rain; regimes of snow and ice, which are natural regulators that store water in winter and release it in summer, would undergo change; and there would be more swings between floods and droughts. It is likely that dams, after a lull of three decades, would witness a comeback.

Current patterns of use and abuse of water resources are resulting in the amount withdrawn being dangerously close to the limit and even beyond; an alarming number of rivers no longer reach the sea. The Indus, the Rio Grande, the Colorado, the Murray-Darling, and the Yellow River – are the arteries of some of the world’s main grain-growing areas. Freshwater fish populations are in precipitous decline; fish stocks have fallen by 30% (WWF for Nature), larger than the fall
in populations of animals in any ecosystem. Fifty percent of the world’s wetlands were drained, damaged, or destroyed in the 20th century; in addition to the fall in the volume of fresh water in rivers, invasion of saltwater into deltas, and change in the balance between fresh water and salt water.

When compared to the global water resources situation, local water shortages are multiplying even faster. Australia has suffered a decade-long drought. Brazil and South America, who depend on hydroelectric power, have suffered repeated brownouts— not enough water to drive turbines. Excess pumping of water from feeding rivers led to the near-collapse of the Aral Sea in Central Asia in 1980; and global water crisis impinges on the supplies of food, energy, and other goods.

The water resources situation in the United States is facing the same trend, with degrading infrastructure built 50 to 100 years ago, such that 17% of treated water is lost due to leaky pipes. In Texas there is an ongoing drought, where ranchers have already lost nearly 1 billion dollars; worst hit are Central Texas and the Hill Country. December 2008–February 2009 has been the driest on record; 60% of the state’s beef cows are in counties with severe to exceptional drought; in 2006, drought-related crop and livestock losses were the worst for any single year, totalling $4.1 billion. The effects of this drought are long-term.

Modern Hydrology and Sustainable Water Development, by Dr S.K. Gupta, is timely and addresses a number of key questions gravitating around the interactions between water, energy, environment, ecology, and socio-economic paradigms. The subject matter of the book will help promote the practice of hydrology focused on sustainable development, with due consideration to linkages between regional economic development, population growth, and terrestrial and lithological hydrologic systems. It states the challenges and opportunities for science, technology, and policy related to sustainable management of water resources development and in turn sustainable societal development.

Introducing the basic concepts and principles of hydrologic science in Chapter 1, the subject matter of the book is organized into 14 chapters, each corresponding to a specific theme and containing a wealth of information. Surface water in lakes, glaciers, streams, and rivers encompassing watershed concepts, stream flow components, hydrograph separation, landform and fluvial geomorphology, and the very wide range of time and space scales that hydrologic theories must span, is dealt with in Chapter 2. Subsurface flow is dealt with in the next two chapters, primarily encompassing groundwater hydrology and well hydraulics. The next chapter deals with methods of computer-aided modelling of surface and groundwater flow systems. Keeping in mind the impact of human activities on the hydro-environment, aqueous chemistry is the subject matter of Chapter 6. Tracer hydrology, developed during the last few decades and playing an important role in modern hydrology, constitutes the subject matter of Chapter 7. Chapter 8 deals with statistical analyses and techniques required for making hydrologic predictions and design. Fundamentals of remote sensing and GIS, another powerful field developed during the last few decades, are described in Chapter 9. Urban hydrologic processes are the theme of Chapter 10. Chapter 11 covers rainwater harvesting and groundwater recharge and is important given recurring water shortages around the world, especially in developing countries. This topic has been receiving a lot of emphasis today. Acknowledging the rightful place of the human dimension in water resource development and management, Chapter 12 goes on to discuss water ethics. A few case studies of field situations, linking many of the aspects discussed in the preceding chapters, are included in Chapter 13. A wrap-up of various chapters, concluding in a holistic manner, is presented in Chapter 14.

The book is well written and well organized. It reflects the vast experience of its author. It will help improve our understanding of the sensitivity of key water quantity and quality management targets to sustainable development. The book is timely and makes a strong case for sustainable development and management in relation to the science and practice of hydrology. It will be useful to students and faculty in engineering, and agricultural, environmental, Earth, and watershed sciences. Water resources planners, managers, and decision-makers will also find the book of value. Dr Gupta is to
be applauded for preparing such a timely book on
hydrology.

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Water is essential not only to people but to all forms of life on Earth. The importance of water for the improvement of health, the production of food, and the support of industry is vital in the rapidly developing world of today. The wider political and social context of water resource development has always been important and will remain so in the future. Three very important examples of this wider context are: (i) the relationship between large-scale irrigation and society; (ii) the role of self-help in rural water supply schemes in developing countries; and (iii) large-scale long-distance transfers of water.

Because of its importance to life and society, water is important to students and professionals in several fields. Chief amongst these are civil engineers with diverse specializations, geologists, agriculture and irrigation engineers, and personnel in charge of municipal and industrial water supplies. Environmentalists and planners often have vital interests in hydrology. Indirectly concerned persons can also be found in the fields of economics, mining and petroleum engineering, forestry, public health, and law amongst others.

Until comparatively recently the approach to hydrology was essentially a pragmatic one. However, during the past few decades, increased demands on water for various applications have stimulated many unsustainable practices of exploitation but, on the other hand, there has been development of new techniques for investigating the occurrence and movement of water in its various forms. Simultaneously, research has contributed to a better understanding of the subject of hydrology and new concepts of resource management have evolved.

Although it is impossible to present the subject of hydrology fitted to such a diversity of interests, the common need of all is an understanding of fundamental principles, methods, and problems encountered in the field as a whole. This book, therefore, represents an effort to make available a unified presentation of the various aspects of the science and practice of hydrology. It is intended to serve both as a reference book and as a textbook. The material derives its scientific underpinning from the basics of mathematics, physics, chemistry, geology, meteorology, engineering, soil science, and related disciplines. The aim has been to provide sufficient breadth and depth of understanding in each subsection of hydrology. The intention is that after going through the book, in the manner of undertaking a course in hydrology, a student should be able to make basic informed analyses of any hydrologic dataset and plan additional investigations, when needed, keeping in mind issues of water ethics and the larger issue of global change and the central position of water therein. Readers with a background in diverse disciples, using the book as a reference work in hydrology, should also be able to find the required information in the context of the practice and the basic science of hydrology. This book is
PREFACE

subdivided into 14 chapters covering the most important conventional and modern techniques and concepts to enable a sustainable development of water resources in any region.

In this book, the utmost care has been taken to present the material free from errors of any kind; some errors and omissions may have escaped editorial scrutiny. If detected, the author requests that these be communicated to him by email: skg.skgupta@yahoo.co.in.

S.K. Gupta
Acknowledgements

This endeavour could not have succeeded without the institutional support of the Physical Research Laboratory (PRL), Ahmedabad - where I learned and researched in hydrology for more than three decades. This is the best opportunity of expressing my gratitude to this great institution. Dr Prabhakar Sharma has painstakingly corrected my manuscript. It is difficult to thank him enough for his encouragement and effort. Dr B.S. Sukhija also reviewed Chapter 7 on hydrologic tracing and provided important input. My patient wife Surekha has been the biggest supporter of this enterprise, always edging me on towards completion - I am indebted to her for all the care and support received. Having a colleague such as Dr R.D. Deshpande, always ready to provide help in every possible manner, has been a very fortunate situation for me.

While all those above have contributed to the successful completion of this project, any omission is solely my responsibility.
A note for students and teachers

The first 12 chapters of this book have been organized into three broad themes:

1) Water, its properties, its movement, modelling and quality (Chapters 1–6);
2) Studying the distribution of water in space and time (Chapters 7–9); and
3) Water resource sustainability (Chapters 10–12).

The first chapter introduces the fundamental concerns and concepts of hydrology. Starting with the basic physical and chemical properties of water, quality parameters, the physics of water flow, and measurement techniques, it also includes the hydrologic cycle. Two broad subdivisions of terrestrial water, namely, visible water sources at the surface and invisible water underground, are also introduced. The second chapter presents the subject of water in lakes, glaciers, and streams, watershed concepts, stream flow components, hydrograph separation, landform, and fluvial geomorphology. Also introduced is the fundamental equation in hydrology, namely, the concept contained in the equation of continuity, equations of free surface flow, saturated and unsaturated flow, and the very wide range of time and space scales that any hydrologic theory must span.

The invisible flow of water, namely, groundwater, is dealt with in the next two chapters. The composite nature of surface and groundwater, aquifer formations and their properties, hydraulic head, saturated flow equations, groundwater measurements, and pollution are described in Chapter 3. Well hydraulics, including steady and unsteady radial flow equations, for unconfined, confined, and leaky aquifers, including the methods of well testing, well losses, and hydraulics associated with partial penetration, form the subject matter of Chapter 4. Methods of surface and groundwater flow modelling, including finite difference, finite element, and analytical element methods, their comparative account, model calibration, parameter estimation, and sensitivity analysis, are discussed in Chapter 5.

Many human activities have adverse impacts on the hydro-environment in ways that decrease the usefulness of the resource substantially, either for human beings or other life forms. Aqueous chemistry is central to understanding: (i) sources of chemical constituents in water; (ii) important natural chemical processes in groundwater; (iii) variations in chemical composition of groundwater in space and time; and (iv) estimation of the fate of contaminants, both in surface and groundwaters, and for remediation of contamination. The focus of Chapter 6 is on principles of chemical thermodynamics, processes of dissolution and/or precipitation of minerals, and on undesirable impacts of human activities, including transport and attenuation of micro-organisms, non-aqueous phase liquids, geochemical modelling, and the relation between use and quality of water.

The second broad theme of studying distribution of water in space and time is addressed in the next three chapters. Fundamentals of the theory and practice of tracer hydrology developed during the last few decades and playing an important role in modern hydrology, particularly when the interest is in obtaining a direct insight into the dynamics of surface and subsurface water, are described.
in Chapter 7. The various tracers from dissolved gases and chemicals to radioactive and stable isotopes of dissolved constituents, including the water molecules themselves, have provided useful tools to understand transport processes, phase changes (evaporation, condensation, sublimation), and genesis of water masses and their quality.

Hydrologists are often required to make predictions on variability and long-term assurance of water availability and hydro-hazards, even as understanding of complex physical interactions and processes that govern natural hydrologic phenomena eludes. Recourse is then taken to understand the inherent statistical distribution of water in space and time. Statistical techniques and probability theory, as relevant to hydrology, form a simple description of statistics to time series analysis, and are the subject matter of Chapter 8.

Availability of many different earth-sensing satellites, with diverse calibrated sensors mounted on sophisticated platforms providing synoptic view and repetitive coverage of a given location, help to detect temporal changes and observations at different resolutions of several parameters important to water resource development, planning, and management. Together with computers, their vastly enhanced data handling capacity and powerful software to manipulate geographical data in the form of a geographical information system (GIS), a new field of analysing digital remote sensing data with other geo-referenced hydrologic/environmental/societal data has evolved. Diverse applications of this intertwined field include estimation of precipitation, snow hydrology, soil moisture monitoring, groundwater hydrology, urban issues, and monitoring of global change. These applications and fundamentals of the two techniques of remote sensing and GIS are described in Chapter 9.

The next three chapters address the broad theme of water resource sustainability. Hydrologic processes occurring within the urban environment where substantial areas consist of nearly impervious surfaces, and artificial land relief as a result of urban developments including formation, circulation, and distribution of water, and techniques of waste treatment and disposal, are discussed in Chapter 10. Also included in this chapter are new approaches and technologies for sustainable urbanization.

Chapter 11 deals with the practice of rainwater harvesting from domestic scale for drinking water supply, to large catchments to support rain-fed agriculture and supplemental irrigation, and for groundwater recharge. Rainwater harvesting together with groundwater recharge using and/or conserving the captured rainwater at or near the place it occurs, offer great promise to improve or sustain water supplies in water-stressed regions.

Not to lose sight of the human dimension in water resource development, major concerns have been described in the form of water ethics in Chapter 12. This chapter also includes a section on global water tele-connections and virtual water that quantifies the amount of water embedded in production of goods and services. The concept of virtual water is very recent and may significantly influence regional and global commodity trade and water allocation for competing demands.

Four case studies from three continents, with field situations, covering regions of high water stress and linking many of the aspects discussed in previous chapters, are included in Chapter 13. Also covered are adaptation measures being employed in each region to mitigate the situation.

A wrap-up of the various chapters, concluding in a holistic manner, on how hydrologic investigations and analyses enable hydrologists to study local, regional, and global water cycle and manipulate and manage it with consideration for human welfare and sustainability, is presented in Chapter 14.

The various chapters are largely independent of each other. Cross references are given only to indicate the linkages between different lines of enquiry. Equations represent mathematical expressions of physical or chemical concepts and most of these have been derived using basic theorems of high school mathematics and calculus. Examples and Tutorials have been included in various chapters to enable students to gain a feel for numbers, units, and dimensions.
Fundamentals of hydrology

Hydrology deals with the scientific study of water, its occurrence, and movement through the Earth-atmosphere system (air, land, and ocean). It is a discipline in the realm of geosciences and derives upon knowledge and techniques from several other fields (i.e., civil engineering, hydraulics, meteorology, geology, forestry, soil science, etc.) to address water availability, in terms of both quantity and quality. In addition, mathematical modeling techniques, both analytical and numerical, are being extensively applied to describe problems of both surface- and ground-water hydrology.

We often perceive liquid water ($\text{H}_2\text{O}$) to be an ordinary substance and mistakenly take its availability for granted. However, it is an extraordinary substance and its unique properties make liquid water the most vital substance for sustenance of all life forms on the Earth. Although we drink it, wash and cook with it, and fish and other aquatic life forms live in it, we nearly always overlook the special relationship it has with our lives. The human body is about two-thirds water and without it we would die of dehydration within a few days. Where there is water there is life, and where water is scarce, life becomes a painful struggle.

Some important chemical and physical properties of water and their crucial relationship with living beings are described in this chapter.

1.1 Properties of water

1.1.1 Chemical properties

Many unique properties of water are largely a result of its chemical structure. Chemically, the water molecule ($\text{H}_2\text{O}$) is a tiny V-shaped molecule with one atom of oxygen bound to two atoms of hydrogen. Indeed, very few molecules in nature are smaller or lighter than water molecules. Two hydrogen atoms are ‘attached’ to one side of an oxygen atom, as shown in Fig. 1.1a, resulting in a water molecule exhibiting electrical polarity with a positive charge on the two hydrogen atoms and a negative charge on the oxygen atom. The polarity of a water molecule allows it to attach to other molecules easily, including another water molecule. Because of attraction between opposite electrical charges, water molecules tend to attract each. As shown in Fig. 1.1b, the side with the hydrogen atoms (positive charge) attracts the oxygen side (negative charge) of a different water molecule.

Water molecules attracting each other cause them to clump together. When a molecule of water is attached to another water molecule, it is called cohesion. When water is attached to other materials, it is called adhesion. If it wasn’t for the Earth’s
Fig. 1.1 (a) The $H_2O$ molecule behaves like an electric dipole, which makes (b) water sticky due to attraction between the molecules. Redrawn from http://ga.water.usgs.gov/edu/waterproperties.html.

gravity, a drop of water would be ball shaped — a perfect sphere. The two properties of cohesion and adhesion give rise to the sticky nature of water.

Water is called the ‘universal solvent’ because it dissolves more substances than any other liquid. This feature also enables water to dissolve and carry minerals and nutrients in runoff, infiltration, groundwater flow, and also in the bodies of living organisms.

1.1.2 Physical properties

Water is the only substance that is found in nature in all three states — liquid, solid (ice), and gas (vapour) — at temperatures normally prevailing on Earth. Water changing from solid to liquid is called melting. When it changes from liquid to the vapour phase, the process is called evaporation. Water changing from vapour to liquid is called condensation (some examples are the ‘moisture’ that forms on the outside of a cold soda water bottle or when the moisture in the air condenses on grass and leaves during early mornings in winter). Frost formation occurs when water changes from vapour directly to its solid form. When water changes directly from the solid to the vapour phase, the process is called sublimation. In fact, the Celsius scale of measuring temperature is derived based on the freezing point of water (at 0°C) and its boiling point (at 100°C at sea level). The large range of temperature, 0–100°C, between its melting and boiling points, enables water to exist in liquid form in most places on the Earth, including regions having extremes of temperature.

Water also has interesting thermal properties. When heated from 0°C (melting point of ice) to 4°C, it contracts and becomes denser; most other substances expand and become less dense when heated. In the case of water this happens only beyond 4°C. Conversely, when water is cooled in the temperature range 4–0°C, it expands. It expands greatly as it freezes, adding about 9% by volume; as a consequence, ice is less dense than water and, therefore, floats on it.

Another unique property of water is its high specific heat ($S$), defined as the amount of heat required to raise the temperature by 1°C per unit mass of the matter. A related quantity is called the heat capacity ($C$) of a given mass of the substance. Specific heat and heat capacities of some common substances are given in Table 1.1, which shows that water has a very high specific heat. This means that water can absorb a lot of heat before it begins to get hot and its temperature changes significantly. This is why water is valuable to industries for cooling purposes and is also used in an automobile radiator as a coolant. The high specific heat of water, present in the air as moisture, also helps regulate the rate at which the temperature of the air changes, which is why the temperature changes between seasons are gradual rather than abrupt, especially in coastal areas.

Table 1.1 Specific heat and heat capacities of some common substances.

<table>
<thead>
<tr>
<th>Substance →</th>
<th>Air</th>
<th>Aluminium</th>
<th>Copper</th>
<th>Gold</th>
<th>Iron</th>
<th>NaCl</th>
<th>Ice</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat ($Jg^{-1} \cdot ^\circ C^{-1}$)</td>
<td>1.01</td>
<td>0.902</td>
<td>0.385</td>
<td>0.129</td>
<td>0.450</td>
<td>0.864</td>
<td>2.03</td>
<td>4.186</td>
</tr>
<tr>
<td>Heat capacity ($J \cdot ^\circ C^{-1}$) for 100 g</td>
<td>101</td>
<td>90.2</td>
<td>38.5</td>
<td>12.9</td>
<td>45.0</td>
<td>86.4</td>
<td>203</td>
<td>418.6</td>
</tr>
</tbody>
</table>

Note: The calorie, defined as the amount of heat required to raise the temperature of 1 gram of water by 1°C, not in use today, has been replaced by the SI-unit, the joule. The conversion is $4.186 J = 1 cal$. 


Water is also unique in another thermal property – latent heat, the heat change associated with a change of state or phase. Latent heat, also called heat of transformation, is a measure of the heat given up or absorbed by a unit mass of a substance as it changes its form from solid to liquid, from liquid to gas, or vice versa. It is called latent because it is not associated with a change in temperature. Each substance has a characteristic heat of fusion, associated with the solid–liquid transition, and a characteristic heat of vaporization, associated with the liquid–gas transition. The latent heat of fusion for ice is \(334 \text{ J (}= 80 \text{ cal}) \text{ per gram}.\) This amount of heat is absorbed by each gram of ice in melting or is given up by each gram of water during freezing. The latent heat of vaporization of steam is \(2260 \text{ J (}= 540 \text{ cal}) \text{ per gram},\) taken up by boiling water at 100°C to form steam or given up during condensation from vapour to liquid, that is, when steam condenses to form water. This is the reason that putting one’s finger in a jet of steam causes more severe burning than dipping it in boiling water at 100°C. For a substance passing directly from the solid to the gaseous state, or vice versa, the heat absorbed or released is known as the latent heat of sublimation.

Although pure water is a poor conductor of electricity, it is a much better conductor than most other pure liquids because of its self-ionization, that is, the ability of two water molecules to react to form a hydroxide ion, \(\text{OH}^-\), and a hydronium ion, \(\text{H}_3\text{O}^+\). Its polarity and ionization are both due to the high dielectric constant of water. In fact, water conducts heat more easily than any other liquid, except mercury. This fact causes large bodies of liquid water such as lakes and oceans to have a uniform vertical temperature profile over considerable depths.

Surface tension is the name given to the cohesion of water molecules at the surface of a body of water. Water has a high surface tension. For example, surface tension enables insects such as water striders to ‘skate’ across the surface of a pond. Surface tension is related to the cohesive properties of water. Capillary action is, however, related to the adhesive properties of water. Capillary action can be seen ‘in action’ by placing a very thin straw (or glass tube) into a glass of water. The water ‘rises’ up the straw. This happens because water molecules are attracted to the molecules on the inner surface of the straw. When one water molecule moves closer to molecules of the straw, the other water molecules (which are cohesively attracted to that water molecule) also move up the inside surface of the straw. Capillary action is limited by gravity and the diameter of the straw. The thinner the straw, the higher will be the capillary rise. Plant roots suck soil water, making use of capillary action. From the roots, water (along with the dissolved nutrients) is drawn through the plant by another process, transpiration. Transpiration involves evaporation of water from leaves, branches, and stems, which results in a pump-like action sucking water from the soil by plant roots and giving it out into the atmosphere in the form of vapour.

The triple point of water refers to a unique combination of pressure / temperature at which pure liquid water, ice, and water vapour can coexist in a stable equilibrium. It is used to define the Kelvin, the SI unit of thermodynamic temperature. Water’s triple point temperature is 273.16 kelvin (0.00°C) and has a pressure of 611.73 pascal (0.0060373 atm). Because the average temperature on the surface of the Earth is close to the triple point of water, it exists in all three phases – gas, liquid, and solid. In the universe, no other planet is known to possess water in all its three phases in abundant quantities.

Fluid properties that control the movement of water are density, pressure, buoyancy, and viscosity. Of these, viscosity is the most significant property, being a measure of the resistance of a fluid to a change of shape or a resistance to flow, and it can be construed as internal friction of a moving fluid. Viscosity can be either dynamic (for fluids in motion) or kinematic (intrinsic). Dynamic viscosity is also a measure of the molecular ‘stickiness’ and is caused by attraction of the fluid molecules to each other. When viewed in the context of intermolecular hydrogen bonding as a cohesive force, it is perhaps surprising that water pours quite smoothly and freely, certainly more freely than, say, honey. Indeed, the viscosity of water is quite modest. So although gravity creates nearly the same stresses in honey and in water, the more viscous honey flows more slowly. Viscosity is temperature dependent but in most cases, due to narrow range of temperature variation, the effect on viscosity is minimal.
The other important factor governing dynamics of a body or hydrodynamics of a fluid is inertia, which is the resistance offered by a body or fluid to any change in its motion. Whether an object or fluid is stationary or moving, it will continue to maintain its state in accordance with Newton’s First Law of motion. The effect of inertia is solely dependent on mass: if scale is increased then size, mass, and inertia increase. Thus, viscous forces dominate at small scales and inertial forces dominate at large scales. To a copepod, sea water is very sticky and it will stop moving immediately if it stops swimming. At this scale, viscosity is the dominant force. To a whale, sea water offers very little resistance and it will keep moving for quite a distance even if it stops swimming. At this scale, inertia is the dominant force. Since viscosity and inertia govern the motion of a fluid, the transition from viscosity-dominated flow to inertia-dominated flow also marks the transition from laminar to turbulent flow.

A summary of hydrologically relevant physical properties of water is given in Table 1.2.

### 1.2 Common water quality parameters

Water sustains plant and animal life. It plays a key role in governing the weather, and helps to shape the surface of the planet through erosion and other processes. The term water quality is used to describe physical, chemical, and biological characteristics of water, usually with reference to its suitability for a particular purpose. Quality of water is of concern, essentially in relation to its intended use. For example, water that is good for washing a car may not be good enough for drinking or may not even support aquatic life. Human beings want to know if the water is good enough for use at home, for serving in a restaurant, for swimming, or if the quality of the water occurring in the area is suitable for aquatic plants and animals.

Standards and guidelines have been established to classify water for designated uses such as drinking, recreation, agricultural irrigation, or protection and maintenance of aquatic life. Standards for drinking-water quality are prescribed to ensure

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molar mass</td>
<td>18.015 g</td>
</tr>
<tr>
<td>Molar volume</td>
<td>55.5 mol l⁻¹</td>
</tr>
<tr>
<td>Boiling point (BP)</td>
<td>100°C at 1 atm</td>
</tr>
<tr>
<td>Triple point</td>
<td>273.16 K at 4.6 torr</td>
</tr>
<tr>
<td>Surface tension</td>
<td>73 dynes cm⁻¹ at 20°C</td>
</tr>
<tr>
<td>Vapour pressure</td>
<td>0.0212 atm at 20°C</td>
</tr>
<tr>
<td>Latent heat of vaporization</td>
<td>40.63 kJ mol⁻¹, 22.6 × 10⁵ J kg⁻¹</td>
</tr>
<tr>
<td>Latent heat of fusion</td>
<td>6.013 kJ mol⁻¹, 3.34 × 10⁵ J kg⁻¹</td>
</tr>
<tr>
<td>Heat capacity (cp)</td>
<td>4.22 kJ kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>78.54 at 25°C</td>
</tr>
<tr>
<td>Viscosity</td>
<td>1.002 centipoises at 20°C</td>
</tr>
<tr>
<td>Density</td>
<td>1 g cm⁻³</td>
</tr>
<tr>
<td>Density maximum</td>
<td>at 4°C</td>
</tr>
<tr>
<td>Specific heat</td>
<td>4180 J kg⁻¹ K⁻¹ (T = 293–373 K)</td>
</tr>
<tr>
<td>Heat conductivity</td>
<td>0.60 W m⁻³ K⁻¹ (T = 293 K)</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>647 K</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>22.1 × 10⁶ Pa</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>1480 m s⁻¹ (T = 293 K)</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>80 (T = 298 °K)</td>
</tr>
<tr>
<td>Refractive index (relative to air)</td>
<td>1.31 (ice; 589 nm; T = 273 K; p = p₀)</td>
</tr>
<tr>
<td></td>
<td>1.34 (water; 430–490 nm; T = 293 K; p = p₀)</td>
</tr>
<tr>
<td></td>
<td>1.33 (water; 590–690 nm; T = 293 K; p = p₀)</td>
</tr>
</tbody>
</table>
that public drinking-water supplies are as safe as possible. The US Environmental Protection Agency (US-EPA) and similar agencies in other countries and/or international agencies such as the World Health Organization (WHO) are responsible for prescribing the standards for constituents in water that are known to pose a risk to human health. Other standards to protect aquatic life, including fish, and wildlife such as birds that prey on fish, have also been notified in most countries. In the following, some of the commonly used water quality parameters are described. In specific cases many other water quality parameters are used, depending on the problem or intended use.

### 1.2.1 Water quality – physical parameters

#### 1.2.1.1 Transparency

The transparency of water is an important quality for drinking purposes, and even more important for aquatic plants and animals that thrive in water. Suspended particles in water behave similarly to dust in the atmosphere, reducing the depth to which light can penetrate. Sunlight provides the energy required for photosynthesis (the process by which plants grow by taking up atmospheric carbon dioxide and releasing oxygen). The depth to which light penetrates into a water body determines the depth to which aquatic plants can grow.

*Transparency* is the degree to which light penetrates in a water column. Two commonly used methods for measuring transparency of water are the Secchi disk and transparency tube. The Secchi disk was first used in 1865 by Father Pietro Angelo Secchi, Scientific Advisor to the Pope, to measure transparency of water. This simple method involves measurement of the depth at which a 20-cm black and white disk lowered into water just disappears from view, and reappears again when raised slightly. An alternative method of measuring transparency is by pouring water into a tube with a pattern similar to that of a Secchi disk on the bottom and noting the depth of water in the tube when the pattern just begins to disappear from view. The Secchi disk is used in deeper, still waters. The transparency tube can be used with either still or flowing waters and can also be used to measure shallow water sites or the surface layer of deep water sites.

#### 1.2.1.2 Water temperature

*Water temperature* is largely determined by the amount of solar energy absorbed by water as well as the surrounding soil and air. More solar insolation leads to higher water temperatures. Effluent water discharged from chemical/manufacturing industries into a water body may also increase its temperature. Water evaporating from the surface of a water body can lower its temperature but only of the thin layer at the surface.

Water temperature can be indicative of its origin. Water temperature near the source will be similar to the temperature of that source (e.g. snowmelt will be cold, whereas most groundwaters are warm). Temperature of surface water farther from its source is influenced largely by atmospheric temperature.

Temperature can be easily measured by using a calibrated thermometer or some other type of calibrated probe and is read while the bulb of the thermometer or probe is still in water. Even though easy to measure, water temperature is a very important parameter because it enables better understanding of other hydrological measurements such as dissolved oxygen, pH, and conductivity.

Temperature influences the number and diversity of aquatic life. Warm water can be harmful to sensitive fish species, such as trout or salmon that require cold, oxygen-rich water. Warm water tends to have low levels of dissolved oxygen. Water temperature is also important for understanding local and global weather patterns. Water temperature changes differently compared to air temperature because water has a higher heat capacity than air. A water body also affects the air temperature of its surroundings through the processes of evaporation, transpiration (from the vegetation that may grow in water), and condensation.

### 1.2.2 Water quality – chemical parameters

#### 1.2.2.1 Electrical conductivity

Pure water is a poor conductor of electricity. However, ionic (charged) impurities present in water,
such as dissolved salts, that enable water to conduct electricity. As water comes in contact with rocks and soil, some of the minerals dissolve in it. Other impurities can enter water bodies through runoff (both surface and subsurface) and/or wastewater discharge.

The amount of dissolved mineral and salt impurities in water is denoted by its total dissolved solids (TDS) content. There are different types of solids dissolved in water, but the most common is sodium chloride (NaCl) - the common table salt. The TDS is specified as parts per million (ppm) or alternatively as mg/l (which is the same as ppm). This indicates how many units of soluble impurities are present in one million units, by mass, of water. For water that is used at home, a TDS of less than 500 ppm is desirable, although water with higher TDS can still be safe to drink. Water used for agriculture should have TDS below 1200 ppm so that salt-sensitive crops are not affected. Manufacturing, especially of electronics equipment, requires water with a very low TDS.

A quick and indirect measure of TDS is the amount of electricity that is conducted across a centimetre length/depth of water column of unit cross-sectional area. Electrical conductivity (EC) is measured as micro-siemens per cm (µS cm⁻¹) which is the same unit as a micro-mho. To convert electrical conductivity of a water sample (µS cm⁻¹) into an approximate concentration of the total dissolved solids (ppm) in the sample, one has to multiply the conductivity value (in µS cm⁻¹) by a suitable conversion factor. The conversion factor depends on the chemical composition of the dissolved solids and can vary between 0.54 and 0.96.

For instance, sugars do not affect conductivity because they do not form ions when dissolved in water. The value 0.67 is commonly used as an approximation so that TDS (ppm) = conductivity (in µS cm⁻¹) × 0.67. It is desirable to use a conversion factor that has been determined for the particular water body instead of the approximation, since the type of impurities between water bodies can vary greatly.

1.2.2.2 Salinity

Another TDS related parameter is water salinity. This is a measure of its saltiness and is expressed as the amount of impurity present in parts per thousand of water (ppt) as against impurity expressed per million parts of water (ppm). The latter is used for relatively fresh waters and estimated by measuring the electrical conductivity. The salinity of the Earth’s oceans averages 35 parts per thousand (ppt); fresh water measures 0.5 ppt or less. Coastal waters and surface waters of the ocean not far from shore can be less salty than 35 ppt due to freshwater input from land surface runoff or rain, or may be more salty due to high rates of evaporation in hot climates. Some seas and inland lakes are also saline. Examples include the Caspian Sea in central Asia, the Great Salt Lake in North America, and several lakes in the Great Rift Valley of East Africa. These water bodies are salty because water flowing into them has no outlet except evaporation, concentrating the dissolved salts. For freshwater bodies that have outlets, salts get flushed out instead of accumulating. Brackish water is saltier than fresh water, but not as salty as sea water. It is found in estuaries and bays where sea water and fresh water mix.

All animals and plants have salts inside the cells of their bodies. The concentration of these salts is about one-third that of sea water. Plants and animals in both fresh and salt water have special mechanisms to maintain a proper salt balance between their cells and the environment around them. Freshwater organisms are saltier than the water they live in. Animals, such as fish in salt water, are less salty than the sea water they live in. Organisms adapted to a given environment cannot be relocated to another without causing them serious injury or even death.

A quick and indirect measurement of salinity involves use of a hydrometer - an instrument that measures the specific gravity of a fluid. A hydrometer is a small float with a graduated scale engraved on its stem. The higher the dissolved salt content, the higher the hydrometer floats compared to its depth in pure water. As the water gets denser, more of the hydrometer is exposed. Marks along the calibrated hydrometer allow reading the specific gravity directly from the hydrometer. In addition to the amount of salt in water, hydrometers are also used to compare the densities of different liquids; for example, the amount of sugar present in fruit juice or the fat content of a milk sample.
Another related water quality parameter is **chlorinity**, which is a measure of the chloride concentration in water. Its usefulness arises from the fact that NaCl is generally the most abundant dissolved salt in natural waters, particularly at the high end of the salinity. In sea water, the following six ions, that are well mixed and found in nearly constant proportions, account for over 99% of the dissolved materials: chloride (\( Cl^- \)) – 55.0%; sodium (\( Na^+ \)) – 30.6%; sulphate (\( SO_4^{2-} \)) – 7.7%; magnesium (\( Mg^{2+} \)) – 3.7%; calcium (\( Ca^{2+} \)) – 1.2%; and potassium (\( K^+ \)) – 1.2%. Therefore, by measuring concentration of the most abundant constituent (\( Cl^- \)), which is also easily measurable by titration, it is possible to estimate total salinity using the equation:

\[
\text{Salinity (ppt)} = \text{Chlorinity (ppt)} \times 1.80655 \quad (1.1)
\]

Measurement of chlorinity by titration is a fairly simple procedure. First an indicator, potassium chromate, is added to a carefully measured volume of the sample. This reagent produces a yellow colour. Silver nitrate solution of known concentration is then added as titrant. Silver reacts with chloride present in the sample to form a white precipitate, silver chloride. When the entire chloride has been precipitated, any excess silver nitrate added forms red-coloured silver chromate, producing the pinkish-orange endpoint. Chloride concentration is calculated from the amount of sample taken and the concentration and amount of silver nitrate used to reach the endpoint.

### 1.2.2.3 Dissolved oxygen

Even though the water molecule (\( H_2O \)) is made up of two hydrogen atoms and one oxygen atom, molecules of oxygen gas (\( O_2 \)) are naturally dissolved in water. The amount of dissolved oxygen (DO) that water can hold (under given conditions) is known as the solubility of dissolved oxygen. Factors affecting the solubility of dissolved oxygen include water temperature, atmospheric pressure, and salinity. Cold water can dissolve more oxygen than warm water. For example, at 25° C, oxygen solubility is 8.3 mg l\(^{-1} \), whereas at 4° C the solubility is 13.1 mg l\(^{-1} \). As the temperature goes up, water releases some of its dissolved oxygen into the air.

Dissolved oxygen is naturally present in water, contributed by plants during photosynthesis, through diffusion from the atmosphere, or by aeration. The amount of dissolved oxygen is also affected by plants and life forms that exist in the water. Just as photosynthesis by terrestrial plants adds oxygen to the air, photosynthesis by aquatic plants contributes dissolved oxygen to water. Water may become supersaturated with oxygen, implying that the dissolved oxygen levels are higher than can be accounted for by its solubility. The excess dissolved oxygen eventually gets released back into the air or is removed through plant respiration. During respiration, biota (fish, bacteria, etc.) consume dissolved oxygen. Without adequate levels of dissolved oxygen in water, aquatic life is suffocated. Dissolved oxygen levels below 3 mg l\(^{-1} \) are stressful to most aquatic organisms. Dissolved oxygen is also consumed during decay of organic matter in water and by some chemical reactions with anthropogenically added impurities.

Dissolved oxygen must be measured at the site (i.e. in situ). Samples cannot be taken back and analysed in the laboratory because the amount of dissolved oxygen in the water can change rapidly after the sample has been collected.

Dissolved oxygen test kits involve two parts – sample preservation (stabilization or fixing) and testing. Preservation involves addition of a chemical to the sample that precipitates in the presence of dissolved oxygen, followed by the addition of a chemical that produces colour in the solution. Testing involves adding titrant solution until the colour disappears. The dissolved oxygen value is calculated from the volume of titrant added.

### 1.2.2.4 Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

A related measure of the amount of dissolved oxygen, in mg l\(^{-1} \), necessary for decomposition of organic matter by micro-organisms (i.e. bacteria or carbonaceous organic pollution from sewage or industrial wastes), is the Biochemical Oxygen Demand (BOD). Natural sources of organic matter include plant decay and litter fall. However, plant growth and decay may be accelerated by human activities when nutrients (due to pollution loading) and sunlight (due to removal of forest cover, etc.) are overly abundant. Oxygen consumed in the decomposition process robs other aquatic...
organisms of the oxygen they need for survival. Organisms that are tolerant of lower levels of dissolved oxygen may replace the diversity of more sensitive organisms. The total amount of oxygen consumed when a biochemical reaction is allowed to proceed to completion is called the Ultimate BOD. Determination of the ultimate BOD is quite time consuming, so the 5-day BOD (referred to as BOD₅) has been universally adopted as a measure of relative pollution. BOD₅ measures uptake of oxygen by micro-organisms at 20°C over a period of 5 days, kept under darkness, and is the most common measure of BOD. Pristine rivers generally have a BOD of less than 1 mg l⁻¹. Moderately polluted rivers have a BOD in the range 2 to 8 mg l⁻¹. Adequately treated municipal sewage has a BOD of about 20 mg l⁻¹. In untreated sewage, the BOD is variable and ranges between 200 and 600 mg l⁻¹. Slurry from dairy farms has a BOD of around 8000 mg l⁻¹ and silage liquor of around 60,000 mg l⁻¹.

Another related parameter, the Chemical Oxygen Demand (COD), is a measure of the chemically oxidizable material present in water and provides an estimate of the amount of organic and reducing material present in water. The basis of measurement of the COD is that nearly all organic compounds can be fully oxidized to carbon dioxide, with a strong oxidizing agent under acidic conditions. There are several to estimate COD. The most common is the 4-hour COD.

It should be emphasized that there is no generalized correlation between the BOD₅ and the ultimate BOD. Likewise, there is no generalized correlation between the BOD and the COD, though the measured values may correlate for a specific waste contaminant in a particular wastewater stream.

1.2.2.5 pH

An important water quality indicator is its pH. It is a measure of the relative amount of free hydrogen and hydroxyl ions present in the water. As hydrogen ions are positively charged, their concentration alters the charge environment of other molecules in solution. For this reason, the pH of water is very important for living beings. Water that has more free hydrogen ions is acidic, whereas water that has more free hydroxyl ions is basic. The pH (log[H⁺]) is reported in ‘logarithmic units’, as -ve logarithm of free hydrogen ions concentration [H⁺]. For pure water [H⁺] = 10⁻⁷ mol l⁻¹, giving it a pH of 7. Each number represents a 10-fold change in the level of acidity/basicity of the water. The pH ranges from 0 to 14; values less than 7 indicate acidity, 7 is neutral, whereas a pH greater than 7 indicates a base. Water with a pH of 5 is ten times more acidic than water having a pH of 6. The pH values of some common liquids are shown in Fig. 1.2. Rain has an acidic pH of about 5.6 because the atmosphere, through which rain drops fall, contains natural carbon dioxide and sulphur dioxide.

![The pH Scale](http://ga.water.usgs.gov/edu/phdiagram.html)