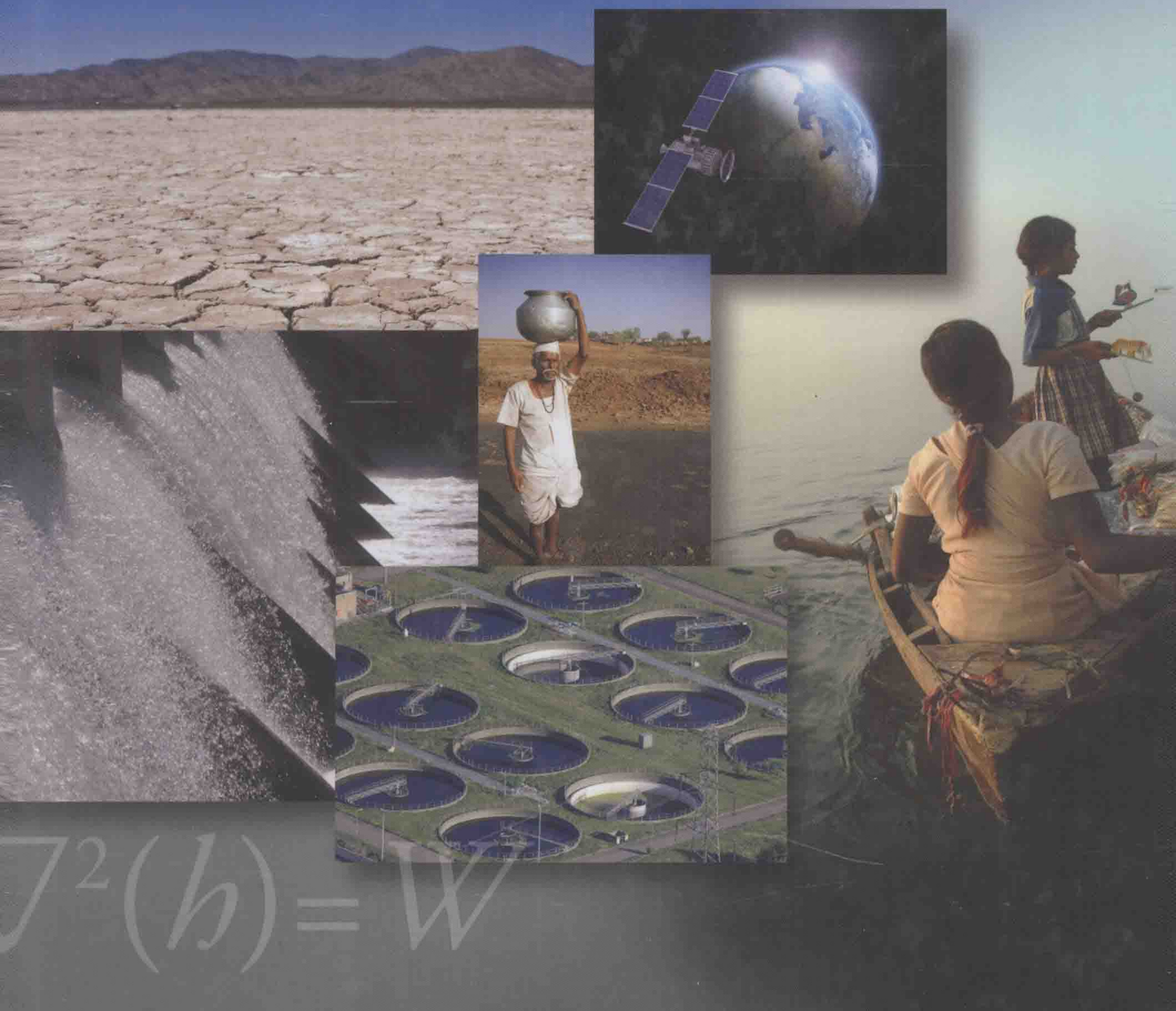
Modern Hydrology
and Sustainable Water Development

S. K. Gupta



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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.

DEDICATION

to

Prof. D. Lal, FRS
His life and work continue to inspire
my academic endeavours.

Foreword

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 $0.6^\circ C$, and it is expected to rise by another $2^\circ C$ 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 decaying 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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Preface

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 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.

Contents