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# APPLIED HYDROLOGY

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## ABOUT THE AUTHORS

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The late Ven Te Chow was a professor in the Civil Engineering Department of the University of Illinois at Urbana-Champaign from 1951 to 1981. He gained international prominence as a scholar, educator, and diplomat in hydrology, hydraulics, and hydrosystems engineering. He received his B.S. degree in 1940 from Chaio Tung University in Shanghai, spent several years in China as an instructor and professor, then went to Pennsylvania State University from which he received his M.S. degree in 1948 and the University of Illinois where he received his Ph.D. degree in 1950. He also received four honorary doctoral degrees and many other awards and honors including membership in the National Academy of Engineering. He was a prolific author, writing his first book at the age of 27 on the theory of structures (in Chinese). He authored *Open-Channel Hydraulics* in 1959 and was editor-in-chief of the *Handbook of Applied Hydrology* in 1964; both books are still considered standard reference works. He was active in professional societies, especially the International Water Resources Association of which he was a principal founder and the first President.

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## PREFACE

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*Applied Hydrology* is a textbook for upper level undergraduate and graduate courses in hydrology and is a reference for practicing hydrologists. Surface water hydrology is the focus of the book which is presented in three sections: Hydrologic Processes, Hydrologic Analysis, and Hydrologic Design.

Hydrologic processes are covered in Chapters 1 to 6, which describe the scientific principles governing hydrologic phenomena. The hydrologic system is visualized as a generalized control volume, and the Reynold's Transport Theorem (or general control volume equation) from fluid mechanics is used to apply the physical laws governing mass, momentum, and energy to the flow of atmospheric water, subsurface water, and surface water. This section is completed by a chapter on hydrologic measurement.

Hydrologic analysis is treated in the next six chapters (7 to 12), which emphasize computational methods in hydrology for specific tasks such as rainfall-runoff modeling, flow routing, and analysis of extreme events. These chapters are organized in a sequence according to the way the analysis treats the space and time variability and the randomness of the hydrologic system behavior. Special attention is given in Chapters 9 and 10 to the subject of flow routing by the dynamic wave method where the recent availability of standardized computer programs has made possible the general application of this method.

Hydrologic design is presented in the final three chapters (13 to 15), which focus on the risks inherent in hydrologic design, the selection of design storms including probable maximum precipitation, and the calculation of design flows for various problems including the design of storm sewers, flood control works, and water supply reservoirs.

How is *Applied Hydrology* different from other available books in this field? First, this is a book with a general coverage of surface water hydrology. There are a number of recently published books in special fields such as evaporation, statistical hydrology, hydrologic modelling, and stormwater hydrology. Although this book covers these subjects, it emphasizes a sound foundation for the subject of hydrology as a whole. Second, *Applied Hydrology* is organized around a

central theme of using the hydrologic system or control volume as a framework for analysis in order to unify the subject of hydrology so that its various analytical methods are seen as different views of hydrologic system operation rather than as separate and unrelated topics. Third, we believe that the reader learns by doing, so 90 example problems are solved in the text and 400 additional problems are presented at the end of chapters for homework or self-study. In some cases, theoretical developments too extensive for inclusion in the text are presented as problems at the end of the chapter so that by solving these problems the reader can play a part in the development of the subject. Some of the problems are intended for solution by using a spreadsheet program, by developing a computer code, or by use of standard hydrologic simulation programs.

This book is used for three courses at the University of Texas at Austin: an undergraduate and a graduate course in surface water hydrology, and an undergraduate course in hydrologic design. At the undergraduate level a selection of topics is presented from throughout the book, with the hydrologic design course focusing on the analysis and design chapters. At the graduate level, the chapters on hydrologic processes and analysis are emphasized. There are conceivably many different courses that could be taught from the book at the undergraduate or graduate levels, with titles such as surface water hydrology, hydrologic design, urban hydrology, physical hydrology, computational hydrology, etc.

Any hydrology book reflects a personal perception of the subject evolved by its authors over many years of teaching, research, and professional experience. And *Applied Hydrology* is our view of the subject. We have aimed at making it rigorous, unified, numerical, and practical. We believe that the analytical approach adopted will be sufficiently sound so that as new knowledge of the field becomes available it can be built upon the basis established here. Hydrologic events such as floods and droughts have a significant impact on public welfare, and a corresponding responsibility rests upon the hydrologist to provide the best information that current knowledge and available data will permit. This book is intended to be a contribution toward the eventual goal of better hydrologic practice.

A special word is appropriate concerning the development of this book. The work was initiated many years ago by Professor Ven Te Chow of the University of Illinois Urbana-Champaign, who developed a considerable volume of manuscript for some of the chapters. Following his death in 1981, his wife, Lora, asked us to carry this work to completion. We both obtained our graduate degrees at the University of Illinois Urbana-Champaign and shared the hydrologic system perspective which Ven Te Chow was so instrumental in fostering during his lifetime. During the years required for us to write this book, it occurred, perhaps inevitably, that we had to start almost from the beginning again so that the resulting work would be consistent and complete. As we used the text in teaching our hydrology courses at the University of Texas at Austin, we gradually evolved the concepts to the point they are presented here. We believe we have retained the concept which animated Ven Te Chow's original work on the subject.

We express our thanks to Becky Brudniak, Jan Hausman, Suzi Jimenez, Amy Phillips, Carol Sellers, Fidel Saenz de Ormijana, and Ellen Wadsworth, who helped us prepare the manuscript. We also want to acknowledge the assistance provided to us by reviewers of the manuscript including Gonzal Cortes-Rivera of Bogotá, Colombia, L. Douglas James of Utah State University, Jerome C. Westphal, University of Missouri-Rolla, Ben Chie Yen of the University of Illinois Urbana-Champaign, and our colleagues and students at the University of Texas at Austin.

A book is a companion along the pathway of learning. We wish you a good journey.

*David R. Maidment*  
*Larry W. Mays*

Austin, Texas  
December, 1987

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**APPLIED HYDROLOGY**

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# CHAPTER 1

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## INTRODUCTION

Water is the most abundant substance on earth, the principal constituent of all living things, and a major force constantly shaping the surface of the earth. It is also a key factor in air-conditioning the earth for human existence and in influencing the progress of civilization. Hydrology, which treats all phases of the earth's water, is a subject of great importance for people and their environment. Practical applications of hydrology are found in such tasks as the design and operation of hydraulic structures, water supply, wastewater treatment and disposal, irrigation, drainage, hydropower generation, flood control, navigation, erosion and sediment control, salinity control, pollution abatement, recreational use of water, and fish and wildlife protection. The role of applied hydrology is to help analyze the problems involved in these tasks and to provide guidance for the planning and management of water resources.

The hydrosociences deal with the waters of the earth: their distribution and circulation, their physical and chemical properties, and their interaction with the environment, including interaction with living things and, in particular, human beings. Hydrology may be considered to encompass all the hydrosociences, or defined more strictly as the study of the hydrologic cycle, that is, the endless circulation of water between the earth and its atmosphere. Hydrologic knowledge is applied to the use and control of water resources on the land areas of the earth; ocean waters are the domain of ocean engineering and the marine sciences.

Changes in the distribution, circulation, or temperature of the earth's waters can have far-reaching effects; the ice ages, for instance, were a manifestation of such effects. Changes may be caused by human activities. People till the soil, irrigate crops, fertilize land, clear forests, pump groundwater, build dams, dump wastes into rivers and lakes, and do many other constructive or destructive things that affect the circulation and quality of water in nature.



### 1.1 HYDROLOGIC CYCLE

Water on earth exists in a space called the hydrosphere which extends about 15 km up into the atmosphere and about 1 km down into the lithosphere, the crust of the earth. Water circulates in the hydrosphere through the maze of paths constituting the hydrologic cycle.

The hydrologic cycle is the central focus of hydrology. The cycle has no beginning or end, and its many processes occur continuously. As shown schematically in Fig. 1.1.1, water *evaporates* from the oceans and the land surface to become part of the atmosphere; water vapor is transported and lifted in the atmosphere until it condenses and *precipitates* on the land or the oceans; precipitated water may be *intercepted* by vegetation, become *overland flow* over the ground surface, *infiltrate* into the ground, flow through the soil as *subsurface flow*, and discharge into streams as *surface runoff*. Much of the intercepted water and surface runoff returns to the atmosphere through evaporation. The infiltrated water may percolate deeper to *recharge* groundwater, later emerging in springs or seeping into streams to form surface runoff, and finally flowing out to the sea or evaporating into the atmosphere as the hydrologic cycle continues.

Estimating the total amount of water on the earth and in the various processes of the hydrologic cycle has been a topic of scientific exploration since the second half of the nineteenth century. However, quantitative data are scarce, particularly over the oceans, and so the amounts of water in the various components of the global hydrologic cycle are still not known precisely.

Table 1.1.1 lists estimated quantities of water in various forms on the earth. About 96.5 percent of all the earth's water is in the oceans. If the earth were a uniform sphere, this quantity would be sufficient to cover it to a depth of about 2.6 km (1.6 mi). Of the remainder, 1.7 percent is in the polar ice, 1.7 percent in groundwater and only 0.1 percent in the surface and atmospheric water systems. The atmospheric water system, the driving force of surface water hydrology, contains only 12,900 km<sup>3</sup> of water, or less than one part in 100,000 of all the earth's water.

Of the earth's *fresh water*, about two-thirds is polar ice and most of the remainder is groundwater going down to a depth of 200 to 600 m. Most groundwater is saline below this depth. Only 0.006 percent of fresh water is contained in rivers. Biological water, fixed in the tissues of plants and animals, makes up about 0.003 percent of all fresh water, equivalent to half the volume contained in rivers.

Although the water content of the surface and atmospheric water systems is relatively small at any given moment, immense quantities of water annually pass through them. The global annual water balance is shown in Table 1.1.2; Fig. 1.1.1 shows the major components in units relative to an annual land precipitation volume of 100. It can be seen that evaporation from the land surface consumes 61 percent of this precipitation, the remaining 39 percent forming runoff to the oceans, mostly as surface water. Evaporation from the oceans contributes nearly 90 percent of atmospheric moisture. Analysis of the flow and storage of water in the global water balance provides some insight into the dynamics of the hydrologic cycle.

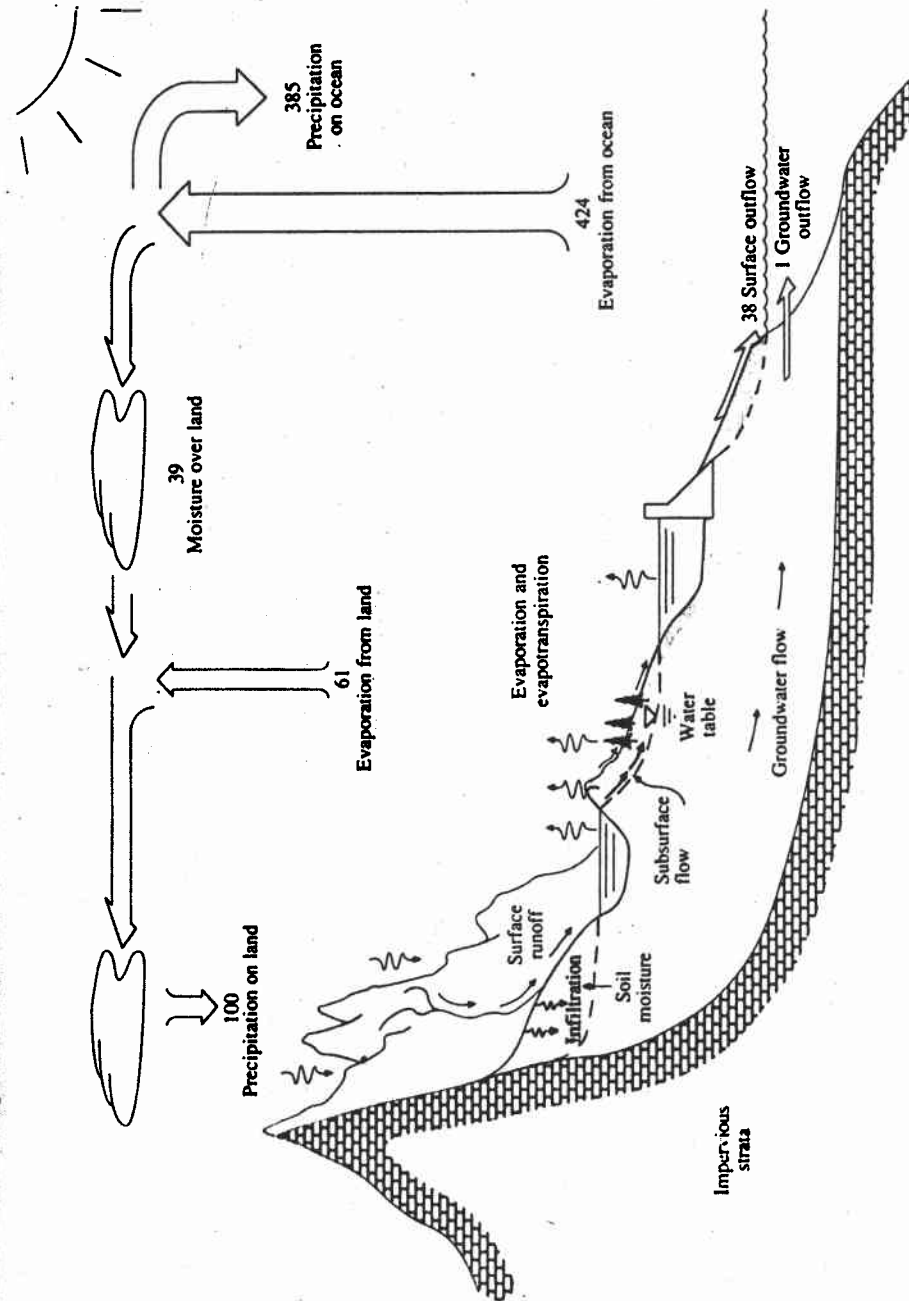


FIGURE 1.1.1 Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land.

TABLE 1.1.1  
Estimated world water quantities

Item	Area (10 <sup>6</sup> km <sup>2</sup> )	Volume (km <sup>3</sup> )	Percent of total water	Percent of fresh water
Oceans	361.3	1,338,000,000	96.5	
Groundwater				
Fresh	134.8	10,530,000	0.76	30.1
Saline	134.8	12,870,000	0.93	
Soil Moisture	82.0	16,500	0.0012	0.05
Polar ice	16.0	24,023,500	1.7	68.6
Other ice and snow	0.3	340,600	0.025	1.0
Lakes				
Fresh	1.2	91,000	0.007	0.26
Saline	0.8	85,400	0.006	
Marshes	2.7	11,470	0.0008	0.03
Rivers	148.8	2,120	0.0002	0.006
Biological water	510.0	1,120	0.0001	0.003
Atmospheric water	510.0	12,900	0.001	0.04
Total water	510.0	1,385,984,610	100	
Fresh water	148.8	35,029,210	2.5	100

Table from World Water Balance and Water Resources of the Earth, Copyright, UNESCO, 1978.

**Example 1.1.1.** Estimate the *residence time* of global atmospheric moisture.

**Solution.** The residence time  $T_r$  is the *average* duration for a water molecule to pass through a subsystem of the hydrologic cycle. It is calculated by dividing the volume of water  $S$  in storage by the flow rate  $Q$ .

$$T_r = \frac{S}{Q} \quad (1.1.1)$$

The volume of atmospheric moisture (Table 1.1.1) is 12,900 km<sup>3</sup>. The flow rate of moisture from the atmosphere as precipitation (Table 1.1.2) is 458,000 + 119,000 = 577,000 km<sup>3</sup>/yr, so the average residence time for moisture in the atmosphere is  $T_r = 12,900/577,000 = 0.022$  yr = 8.2 days. The very short residence time for moisture in the atmosphere is one reason why weather cannot be forecast accurately more than a few days ahead. Residence times for other components of the hydrologic cycle are similarly computed. These values are averages of quantities that may exhibit considerable spatial variation.

Although the concept of the hydrologic cycle is simple, the phenomenon is enormously complex and intricate. It is not just one large cycle but rather is composed of many interrelated cycles of continental, regional, and local extent. Although the total volume of water in the global hydrologic cycle remains essentially

TABLE 1.1.2  
Global annual water balance

		Ocean	Land
Area (km <sup>2</sup> )		361,300,000	148,800,000
Precipitation	(km <sup>3</sup> /yr)	458,000	119,000
	(mm/yr)	1270	800
	(in/yr)	50	31
Evaporation	(km <sup>3</sup> /yr)	505,000	72,000
	(mm/yr)	1400	484
	(in/yr)	55	19
Runoff to ocean			
Rivers	(km <sup>3</sup> /yr)	—	44,700
Groundwater	(km <sup>3</sup> /yr)	—	2200
Total runoff	(km <sup>3</sup> /yr)	—	47,000
	(mm/yr)	—	316
	(in/yr)	—	12

Table from World Water Balance and Water Resources of the Earth, Copyright, UNESCO, 1978.

constant, the distribution of this water is continually changing on continents, in regions, and within local drainage basins.

The hydrology of a region is determined by its weather patterns and by physical factors such as topography, geology and vegetation. Also, as civilization progresses, human activities gradually encroach on the natural water environment, altering the dynamic equilibrium of the hydrologic cycle and initiating new processes and events. For example, it has been theorized that because of the burning of fossil fuels, the amount of carbon dioxide in the atmosphere is increasing. This could result in a warming of the earth and have far-reaching effects on global hydrology.

## 1.2 SYSTEMS CONCEPT

Hydrologic phenomena are extremely complex, and may never be fully understood. However, in the absence of perfect knowledge, they may be represented in a simplified way by means of the *systems* concept. A system is a set of connected parts that form a whole. The hydrologic cycle may be treated as a system whose components are precipitation, evaporation, runoff, and other phases of the hydrologic cycle. These components can be grouped into subsystems of the overall cycle; to analyze the total system, the simpler subsystems can be treated separately and the results combined according to the interactions between the subsystems.

In Fig. 1.2.1, the global hydrologic cycle is represented as a system. The dashed lines divide it into three subsystems: the *atmospheric water system* containing the processes of precipitation, evaporation, interception, and transpiration; the *surface water system* containing the processes of overland flow, surface runoff, subsurface and groundwater outflow, and runoff to streams and the ocean; and