Hydrology and Water Resources Engineering

Alpha Science

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Alpha Science International Ltd.

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To the memories of those engineers and scientists,
who have enhanced our knowledge on water
resources and hydraulic engineering

PREFACE

Water is precious for life on earth. There is an ever increasing demand for the supply of fresh water to the various sectors of the human needs. This has given rise to the problem of optimal management of water resources potential on all parts of the world, more so, in a developing country like India, where the distribution of the resource is highly uneven both in space and time. Hydrology plays the central role in the development and management of water resources and therefore, the protection of environment. As a result, hydrology forms a part of curricula at the undergraduate and postgraduate levels in agriculture, civil engineering, environmental engineering, geology and earth sciences, forestry and meteorology.

Based on my experience as an engineer in the water resources design, planning, development and management for more than a decade and a long teaching experience thereafter, I felt the need for a textbook written in simple and lucid style that can be easily followed by students who have not had an opportunity of the exposure to the subject before. A student can understand most parts of this book himself. At the same time, the book can serve as a source of information to the engineers and other professionals dealing with water resources planning, development and management. Therefore, the chapters have been designed and developed in a systematic way. The materials for the book are mostly taken from the class notes prepared for the graduate students and at the same time utilising my decade long experience from the field problems. Therefore, emphasis have been given on the applicability of the text materials to the field situations. Using data from the field, a large number of hydrologic design problems have been worked out for each concept of the chapters to illustrate the analysis and design procedure.

The text is arranged in ten chapters. Chapter 1, besides a brief resume to the history of hydrology, introduction to meteorology, discusses hydrologic cycle, cloud and availability of water on earth. Since statistics and probabilities play an important role in the estimation of hydrologic parameters, the same have been discussed in Chapter 2. Chapter 3 is essentially devoted to the precipitation, its measurement and analysis. Measurement and estimation of hydrologic losses like evaporation, evapotranspiration, interception, depression storage and infiltration are covered in detail in Chapter 4. Groundwater forms a major component in hydrologic cycle and therefore, the hydrologic aspects of ground water are discussed in Chapter 5. In Chapter 6, the aspects of stream flow measurement and the rainfall runoff process are discussed at length. Hydrographs are discussed in Chapter 7. Estimation of design flood for various types of catchments is given in Chapter 8, while Chapter 9 covers various methods of channel and reservoir routing. In Chapter 10, reservoir sedimentation and the aspects of cost benefit have been discussed. Sufficient problems are given at the end of each chapter for practice. Important references have been cited at the end of the book.

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Any suggestion in improving the book will be thankfully received and will be incorporated in the next edition.

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CONTENTS

Chapter One

Introduction

1.1 GENERAL

Hydrology deals with the origin, distribution and circulation of water in different forms in land phases and atmosphere. It is an interdisciplinary subject starting with meteorology through agronomy, forestry, geology, hydraulics and finally oceanography. Statistics, physics and chemistry help to formulate and understand the subject more conceptually. Solutions to hydrologic problems are usually carried out by borrowing techniques from several disciplines. Depending on the treatment of data, hydrology can be divided into various sub-branches as shown in Fig. 1.1.

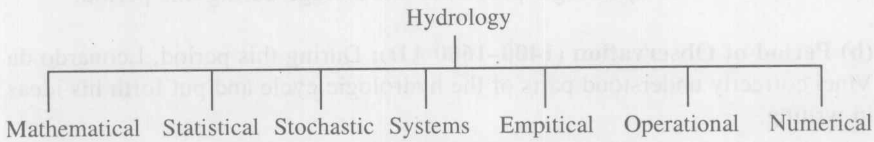

Fig. 1.1 Division of Hydrology

Broadly, hydrology is classified into two groups. The 'scientific hydrology' is concerned mainly with academic aspect, whereas, the 'engineering' or 'applied' hydrology includes: (i) estimation of water resources; (ii) study of transmission process like precipitation, evaporation, runoff and their interdependence; (iii) understanding the properties of water in nature and (iv) dealing with natural problems like droughts and floods. The distribution of water potential in India is highly uneven both in space and time. With the growth of population, the demand of water has also increased to many fold. The science of hydrology can be effectively employed to overcome these difficulties. Therefore, a lot of research and developmental opportunities do exist in this comparatively new branch of science. We would describe some of the aspects of hydrology, which should help a student to understand the subject. The book should also help field engineers or hydrologists to solve their problems connected with water resources engineering.

1.2 HISTORY OF HYDROLOGY

There is no evidence of the date of construction of the first water resource project on the earth. Water being the chief ingredient in life, all ancient civilisations flourished only near the sources of water and then probably collapsed either when the water supply failed or when they were devastated by floods. Man's quest for knowledge, his capacity for innovation and adventure have contributed greatly to his efforts at understanding and exploiting this resource right from Indus-valley civilisation. Archaeological evidence of the existence of wells in Mohenjodaro (3000 BC), the diversion weirs on the river Nile by king Means (3000 BC) and the kanats for irrigation in Persia were the few structures men believed to have constructed in the ancient times. Reference can also be found in Vedic literature (3000 BC), Arthashastra by Chanakya (300 BC), Brihatsamhita by Varahamihira (505–587 AD) and in lots of other ancient writings about the availability, measurement and use of the surface and ground water. In India, during Chanakya's period, kings probably maintained a network of gauges in their kingdoms for tax collection. Writings of ancient thinkers like Aristotle (350 BC), Plato (350 BC), Vitruvius (100 BC) and others suggest their scientific thinking of various hydrologic processes. Following Chow, the history of hydrology can be classified into the following eight periods.

(a) Period of Speculation (Prior to 1400 AD): During this period, many hydraulic structures were known to have been constructed. The important being the Arabian wells, Persian Kanats, Egyptian and Mesopotamian irrigation projects, Roman aqueducts, water supply and drainage projects in Indus valley and the Chinese irrigation systems. Vitruvius was probably the first great philosopher to think rationally about the hydrologic processes and storage during this period.

(b) Period of Observation (1400–1600 AD): During this period, Leonardo da Vinci correctly understood parts of the hydrologic cycle and put forth his ideas in writing.

(c) Period of Measurement (1600–1700 AD): In this century measurement of rainfall, runoff, evaporation and study of artesian wells were taken up by different thinkers. Correct predictions of some hydrologic phenomena were also made.

(d) Period of Experimentation (1700–1800 AD): New discoveries like Bernoulli's piezometer, Pittot tube, Waltman's current meter, Borda's tube, Bernoulli's theorem, Chezy's formula and D'Alembert's principle were made during this period. All these helped to quantify the total water resource potential of the world.

(e) Period of Modernisation (1800–1900 AD): Substantial contributions were made in the fields of both ground and surface water hydrology during this century. Important contributions being Darcy's law, Poiseuillie's equation of capillary flow, Dupuit-Thiem's well formula, Weir-discharge formula, Kutter's determination of Chezy's equation, Manning's equation, Price current meter and Dalton's law of vapour pressure.

(f) Period of Empiricism (1900–1930 AD): Thirty years following the early part of 20th century saw the science of hydrology largely empirical. A number of formulae were proposed and various governments undertook massive efforts in setting up organisations for measurement of hydrological parameters quantitatively in most of the important river basins of the world.

(g) Period of Rationalisation (1930–1950 AD): Most of the present concepts in hydrology date back to 1932, the year in which Le Ray K. Sherman rationalised the concept of hydrology by demonstrating the use of Unit Hydrograph for translating the rainfall excess into runoff hydrograph. The other great contributions during this period were Horton's (1933) determination of rainfall excess from infiltration characteristics, Theis (1935) well hydraulics, Gumbel's (1941) extreme value frequency distribution, Bernard's introduction of meteorology to hydrology and Einstein's theory of sediment load. A lot of laboratories of international repute were also established.

(h) Period of Theorisation (Since 1950): The advent of modern high speed computing machines, sophisticated instrumentation and emergence of modern fluid mechanics helped greatly in the formulation of new theories on hydrology. Many hydrologic activities of international level were also established. Some notables are Water Resources Development Centres (WRDC), World Meteorological Organisation (WMO), International Association of Scientific Hydrology (IASH) etc. In 1961 an International Hydrologic Decade (IHD) was proposed by IASH to co-ordinate international research and training programs in hydrology.

In India, National Institute of Hydrology (NIH) and Department of Hydrology at the University of Roorkee (besides other institutions) are promoting research and training programs and co-ordinating international activities.

1.3 METEOROLOGY (*METEOROS*-LOFTY; *LOGOS*-DISCOURSE)

It is that branch of science which deals with the entire gaseous envelope around the earth. Hydrology starts with precipitation of water vapour on the earth's surface. Therefore, it is desirable to know something about the factors, which bring about these changes. Atmosphere (*atoms*-vapour; *spheria*-sphere) is the gaseous envelope of the earth. It is a mixture of gases and the water vapour is of special interest to the hydrologists. The atmosphere exerts a weight of about 1.033 kg/cm^2, which is equivalent to 10.3 m depth of a water column. The atmospheric pressure is one atom (~ 1013.25 mb). Though water vapour in the atmosphere is limited to a few kilometres from earth's surface, it may be required to know the division of atmosphere into concentric layers. The layers with the variation of temperature and pressure across it are shown in Fig. 1.2.

Atmosphere enveloping the earth is divided into five concentric layers. *Troposphere* (a layer just above the earth's surface) contains all moisture, dust and almost three-fourth of total air mass. *Tropopause* is the top of troposphere, which separates it from the *stratosphere* layer above it. The height of troposphere varies from 8 km at poles to 16 km at the equator. In the stratosphere, temperature is almost constant. *Mesosphere* is just above stratosphere. Temperature in this zone is always higher than ground surface due to absorption of heat from sun's radiation. The fourth layer is known as *ionosphere*, which is 70–80 km above the earth's surface and is responsible for reflecting ordinary radio waves. This layer has a high concentration of free electrons. The outermost shell is called *exosphere*, where atmosphere loses all its properties. A sound knowledge of troposphere is important for a hydrologist as the weather is confined to this layer only.

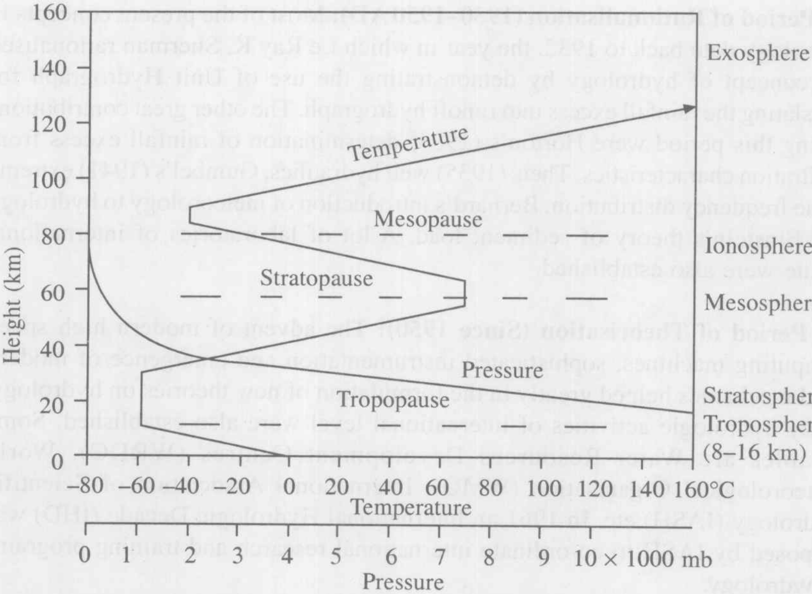

Fig. 1.2 Variation of Temperature and Pressure with Height from Earth's Surface

1.3.1 Lapse Rate

The rate at which temperature decreases with the increase of altitude at any particular time is called lapse rate. When a mass of air at the surface of earth is heated up, it expands and becomes lighter than the surroundings and then rises. Similarly, heavier air at higher altitudes sinks and contracts due to increase in pressure. Though no heat is added or subtracted from the system, the change in temperature takes place due to expansion and contraction only and this change in temperature for the dry air, known as dry adiabatic lapse rate is 10°C/km. The dry adiabatic lapse rate is higher than the normal air lapse rate which varies at the rate of 6.5°C/km up to the first 10 km from earth's surface and then almost at zero rate for the next 10 km. *Inversion* is the reverse of lapse rate. As air mass rises, it loses heat with altitude and at certain stage there is no further decrease in temperature even if it rises further unless there is condensation of some water vapour. This temperature at which the air mass just becomes saturated, if cooled at constant pressure without any moisture added or removed from it, is called *dew point*. After condensation level, the air mass continues to ascend due to the latent heat of condensation added to it. This change in temperature is called adiabatic saturation lapse rate, which is between 3 and 10°C/km of the altitude change.

Sometimes the term *normal temperature* meaning the mean of 30 records of the corresponding period picked up from each year is used. Temperature data published by India Meteorological Department (IMD) contains daily, weekly, monthly or annual normal records. For example, the normal temperature of 1st January is obtained by taking the average of 30 years of 1st January data from say 1970 to 1999. This may be either the minimum or maximum temperature for the day. On the other hand, the term 'mean' refers to the daily averages of maximum and minimum temperatures. For example, for 1st January 1999, the average of maximum and minimum temperatures for the day is the mean temperature.

1.3.2 Pressure

Atmospheric pressure is the pressure exerted by the gases of the atmosphere on the earth's surface due to their own weight. It decreases uniformly from the surface of earth and the rate of decrease depends on temperature and lapse rate. Again due to excess heat, air at the equator belt rises and sinks at around 30° latitude belts. Therefore the equator belt is of low pressure zone and the 30° north and south belts are the higher pressure zones (sub-tropical belt). At 60° north and south, the higher pressure air coming from poles meet the air coming from sub-tropical high pressure zones and causes it to rise to form a low pressure belt at this zone. Due to earth's rotation around its own axis the movement of a parcel of air is affected (coriolis force). This force, along with the fictional resistance on the earth's surface, forces the air at an angle across the isobars causing a counter clockwise movement around low pressure centres and clockwise movement around high pressure centres in the north hemisphere. A reversal of the situation can be seen in the southern hemisphere. At equator, the speed of the earth is 1670 km/h from west to east and at 60° latitude it is about 830 km/h. From the knowledge of physics, we can calculate a theoretical velocity of 2505 km/h of a parcel of air at rest, relative to earth's surface at the equator and moving east–northward direction to 60° latitudes. However, this does not happen because of frictional resistance the air has to overcome at the surface due to features of the earth and air densities. An oversimplified pattern of air circulation on earth's surface is shown in Fig. 1.3.

Isobar (line joining points of equal pressure) is drawn on a weather map in such a way that the lines pass through points of equal sea level pressure. A *front* is the border region of adjacent air masses, normally, the colder air forms a wedge above which warmer air ascends. The ascending warmer air cools with the lapse rate leading to the formation of cloud and precipitation. Front is of four types. A cold front is formed at the boundary between the advancing cold air and retreating warm air (Fig. 1.4a), whereas in a warm front, the advancing warm air meets the retreating cold air (Fig. 1.4b). In a stationary front, both the warm and cold masses cease to move. When the two cold fronts meet, the region between two fronts become warmer. This situation is conducive for the formation of cyclones. Both fronts get elevated and the condition is called occluded front.

1.3.3 Water Vapour

It is that gaseous stage of water which can be condensed. The amount of water vapour in the atmosphere is a meagre 1 part in 100000 of all the water on earth but it plays a vital role for the sustenance of life on earth. A large amount of water passes through the atmosphere due to the continuous process of vaporisation and condensation taking place globally. The process by which liquid is converted to vapour is called *evaporation* or *vaporisation*. *Condensation* is the reverse