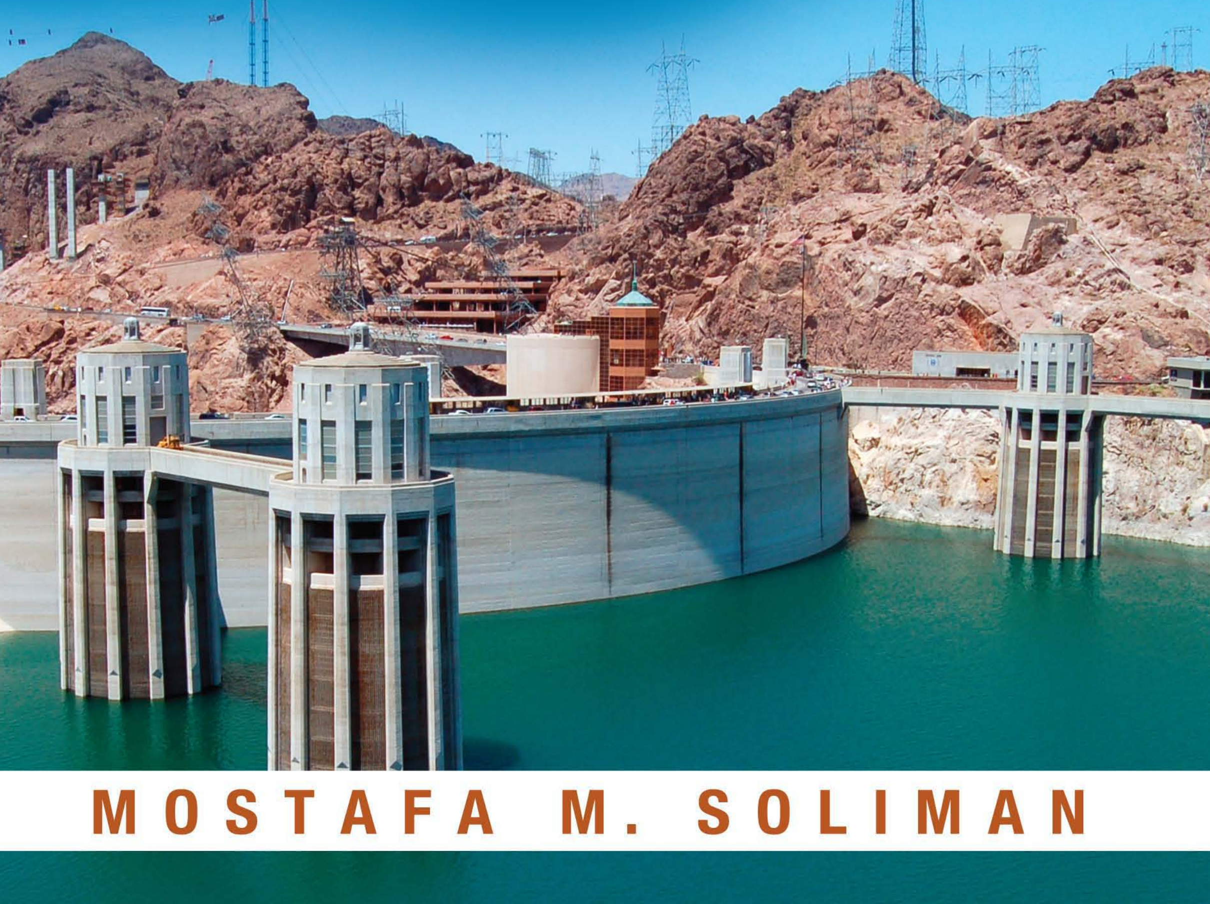
ENGINEERING HYDROLOGY of ARID and SEMI-ARID REGIONS



MOSTAFA M. SOLIMAN

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MOSTAFA M. SOLIMAN

Professor, Faculty of Engineering
Ain Shams University
Cairo, Egypt

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Preface

The demand for water is increasing worldwide due to social and economic development activities. Meeting the development goals of the new millennium puts additional pressure on natural water systems, especially in countries located in arid and semi-arid regions of the world. Countries facing water stress are trying to rely on alternative sources to augment their water availability, provide safe and adequate water supply, and meet the increasing food demand for an increasing population.

Natural scarcity is due to low rainfall, aridity, high evaporation rates, and widely random temporal and spatial variation in the occurrences and distributions of surface and groundwater resources. These factors make it difficult to achieve a reliable water supply.

This already difficult water situation is further complicated by man-made factors, such as increased pollution levels, wasteful utilization, limited databases, and a shortage of institutional and human resources in most countries.

Rainfall is usually less predictable; large floods are common; and recharge events are difficult to quantify. In addition, much water is abstracted from nonrenewable aquifers. Such degradation of water quantity at both national and regional levels is further exacerbated by a lack of regulatory and legal institutions to manage, protect, and monitor water resources, especially in developing countries. The effect of global warming on climate change and its possible effect on rainfall will also be discussed.

An adequate scientific understanding of the hydrologic processes in arid and semi-arid areas is the key component to formulate and implement integrated management approaches in catchment systems. These objectives can be achieved by undertaking basic and applied research and sustained education and training programs. Additional results can be achieved by taking advantage of new techniques in hydraulic structures and instrumentations with the support of adequate financial resources and human resources development.

Research efforts and networking during the last two decades have contributed to the enhanced state of knowledge of the hydrology of arid and semi-arid areas, especially the watershed system. Initial efforts in these directions came from related books enhancing the knowledge of hydrologic principles and their application to satisfy the needs of civil engineering students and hydrologists. These objectives are being achieved through capacity-building processes, education, and training, as well as institutional development.

Watershed systems in arid regions form ephemeral streams that dry up completely in rainless periods. These streams are called wadis in Arab regions. This term is increasingly recognized as an international name used in most hydrologic publications all over the world. Yet, despite their great role as a vital source of water supply, as well as the threat of catastrophic floods in many countries, scientific understanding and knowledge about wadis' hydrologic processes are poor in most of the arid and semi-arid countries all over the world.

The book begins with an introduction to the field of engineering hydrology of arid and semi-arid regions in Chapter 1. Chapter 2 covers the meteorological processes and hydrology in arid and semi-arid zones. Chapter 3 covers precipitation, and Chapter 4 presents precipitation losses. Chapter 5 covers the catchment characteristics and runoff estimation methods. Chapter 6 covers stream flow measurements, and Chapter 7 presents stream flow hydrographs. Chapter 8 covers flood routing, while Chapter 9 covers groundwater hydrology, including the basic equations of groundwater flow, analytic solutions describing flow in aquifers, pumping tests, and salt water intrusion. Chapter 10 covers sediment yield in arid and semi-arid watersheds and its streams. Chapter 11 discusses the design of hydraulic structures that serve to protect and manage the water resources systems in arid and semi-arid regional catchments. Chapter 12 presents some selected case studies in different arid and semi-arid watersheds in order to demonstrate a variety of engineering water resources management projects. All chapters include solved problems to demonstrate and explain the usage of different theories and equations presented in these chapters.

The appendices include Appendix A, conversion tables; Appendix B, a glossary of important hydrologic terms; Appendix C, statistic and stochastic analysis theories; and Appendix D, a software manual for hydrologic models designed by the author, including an example explaining how to use the hydrologic model in order to get the flood hydrograph of a catchment in a simple way. The software can be downloaded from the publisher's site with permission.

This textbook can serve both undergraduate and graduate students who are studying or researching the hydrologic sciences. It can also be used as a guide for both hydrologic professionals and hydraulic engineers.

Prof. Dr. Mostafa M. Soliman

Author

Mostafa M. Soliman received his Bachelor of Science in civil engineering from Cairo University in 1953, his Master of Science in civil engineering from Colorado State University in 1957, and his PhD in civil engineering from Utah State University in 1959.

He has published several books in the field of irrigation engineering and was a senior author of *Environmental Hydrogeology* (1998) and of the second edition of the same book, published by Lewis/CRC of New York. This book is a highly recommended text used by many universities.

Dr. Soliman has acted as a chairman of six International Conferences on Environmental Hydrology (in 1995, 1999, 2002, 2005, 2007, and 2009) in Cairo, Egypt, and he was also the editor of those conference proceedings.

Dr. Soliman has undertaken a variety of assignments in the area of water sciences. His contribution to the field of water resources, hydrologic modeling, and its uses include promoting evolution in the fields of water resources' quality protection, reuse, and capacity building in the Middle East, Europe, and the United States. He has held several academic and administrative positions as a lecturer, assistant professor, and professor at the University of Ain Shams, followed by his appointment as department head of irrigation and hydraulics. Later, he was appointed as the chairman of environmental engineering at the Institute of Environmental Studies and Research at the university. He had also worked as a visiting professor at Washington State University in Pullman, Washington, for more than 2 years, the University of Mississippi, and the University of Alabama. He lectures short courses in hydrological sciences at many international institutes sponsored by UNESCO in Europe and the Middle East.

As a consultant, Dr. Soliman has emerged as one of Egypt's most progressive engineers, combining a sound understanding of problems and technology with an enlightened vision of what the region needs and which developments offer promise. He has experience in research and consultation with both UNESCO and FAO and a substantial share in designing major reclamation projects, pumping stations, and their hydraulic structures. He also conducts hydrological research in Egypt and other Arab countries.

Dr. Soliman has received numerous awards, including the Ideal Engineer Medal from the Egyptian Syndicate of Engineers (1984), the Arid Land Hydraulic Prize from the American Society of Civil Engineers (1998), the Selected Distinguished Member Award from the American Society of Civil Engineers (2000), the Ain Shams University Award in Engineering Sciences (2003), and the Egyptian

Academy of Research Sciences and Technology Award in Advanced Engineering Technology Sciences (2007). Dr. Soliman also holds the following volunteer positions: distinguished member of the American Society of Civil Engineers, president of the American Society of Civil Engineers (Egypt section), president of the Egyptian Society of Irrigation Engineers, member of the Board of Egyptian Society of Engineers, the Board of Directors of the National Water Research Center, and member of many other scientific societies for many years, such as the Academy of Science, the American Scientist Society, the American Institute of Hydrology, the International Association of Hydrological Sciences, the International Association for Hydraulic Research, and the International Association of Hydrogeology.

1 Introduction

1.1 GENERAL REMARKS

Water is considered a scarce resource in arid and semi-arid areas, which occupy approximately one-third of the land, yet the demand for water is growing as populations expand and economies develop. At the same time, threats to existing water resources are also increasing due to pollution, overexploitation of resources, and climate change. The importance of water to the natural environment and the need for conservation of resources to protect valuable ecosystems are increasingly recognized in arid and semi-arid areas. Water is also a major hazard. Floods remain one of the most damaging and dangerous natural hazards globally, and flood risk is increasing with increasing development, as housing, industry, and infrastructure, which are increasingly encroaching on flood-prone areas, expand. Climate change is expected to lead to intensification of extreme events and further increases in risk. This will be discussed in Chapter 2.

Although there is no agreement among hydrologic experts on the distinct classifications of arid and semi-arid regions based on their annual rainfall, the following categories may be generally identified (Soliman 2008):

1. Areas where the annual total rainfall is less than 70 millimeters per year and evaporation exceeds the yearly rainfall may be classified as extreme desert areas. Two-thirds of the Middle East region can be classified as desert.
2. Areas where the annual total rainfall is between 70 and 200 millimeters per year with sparse vegetation are called arid regions.
3. Areas where the annual total rainfall is between 200 and 450 millimeters per year are classified as semi-arid regions. The Mediterranean Sea coast is classified as a Mediterranean zone with rainy and moderately warm winters and dry summers and can be considered to be between arid and semi-arid regions.

Clearly, there is an unprecedented need for effective, appropriate, and sustainable management of water to protect populations and the natural environment and to provide secure water supplies. This requires a sound foundation of scientific understanding of the natural hydrologic systems and appropriate tools to support water management and optimize the sustainable use of water resources.

Hydrology principles generally relate to the waters of the earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with the environment, including their relation to living things. The domain of hydrology embraces the full life history of water on earth. Engineering hydrology includes segments pertinent to the design and operation of engineering projects for the control and use of water. The boundaries between hydrology and other earth sciences such as meteorology, oceanography, and geology are indistinct, and there is no need to define them rigidly. Likewise, the distinctions between engineering hydrology and other branches of applied hydrology are vague. Indeed, an engineer owes much of his or her present knowledge of hydrology to agriculturists, foresters, meteorologists, geologists, and others in a variety of fields. With this definition, we may think of hydrology as being bounded above by meteorology, below by geology, and at land's end by oceanography, but without any distinct lines of demarcation. The several sciences are not blocks to be fitted into individual compartments, and perhaps none of them represents a distinct body of subject matter as much as it represents a different point of view. The entire cycle of water movement, from clouds to earth to sea and back to clouds, is of interest to meteorologists, hydrologists, geologists, and oceanographers alike, but each treats it from a different aspect. Meteorologists concern themselves primarily with the precipitation phase of the cycle; they analyze the movements of air masses and make short-term predictions of temperature and wind and the occurrence of precipitation. Hydrologists measure the flow of streams and groundwater, analyze the regimen of rivers, and then, on the basis of their own measurements and the predictions of meteorologists, they make both short- and long-term quantitative predictions of flood, drought, and normal flow; hydrologists measure the water intake into the soil and groundwater reservoirs and are concerned with evaporation and transpiration losses; they also study the methods of developing water resources and predict the effects of proposed improvements on the regimen of streams and the groundwater reservoir. Geologists (LaMoreaux et al. 2008) focus on the earth's structure and consider water both a mechanical and chemical agent that produces changes in physiography and internal structure by erosion, transportation, and deposition of sediment, freezing and thawing, and chemical action; hydrologists depend on geologists for information on the probable location, extent, and source of recharge of groundwater reservoirs. Oceanographers are concerned largely with tidal movements, wave actions, ocean currents, and similar phenomena.

Clearly, all these sciences have a large body of subject matter in common; the list of related sciences could be extended still further if we so choose. Thus, meteorologic, hydrologic, and geologic data provide the basis for climatology, which, with the introduction of biological aspects, blends into plant ecology; and from ecology, it is but a step to agronomy. To complete the cycle, hydrologists make use of their knowledge of ecology to deduce the depth to groundwater, seasonal fluctuations in the groundwater table, and probable rates of evapotranspiration and work with agronomists to develop adequate conservation practices that will protect the soil from erosion and the streams from silting and will provide water where it is needed and remove it where it is in excess.

1.2 ENGINEERING HYDROLOGY FOR ARID AND SEMI-ARID REGIONS

A brief review of some of the practical applications of engineering hydrology (Linsley et al. 1975) may provide a helpful background for a more detailed study of the subject. In this section, we consider a few of its uses related to structural design, water supply, irrigation, flood control, erosion control, and environmental impacts on water resources, and finally its applications on water resources management (Mays 2005; Chin 2006) in arid and semi-arid regions.

1.2.1 Structural Design

On highways and railroads that cross a stream of a catchment in an arid or semi-arid area, the construction cost of crossing works such as bridges, culverts, or Irish crossings adds up to an appreciable part of the total cost of such projects. Sometimes, culverts or bridges are located so that we need not expect them to be destroyed by a flood that exceeds, even by a considerable amount, their design capacity; in such cases, a temporary interruption of service due to flooding of the road or rails is only an inconvenience. Figure 1.1 illustrates the flash flood water damage at one of the crossing works a stream in Sinai, Egypt, which is an arid region where there is occasional rainfall during winter (Kotb and El Belasy 2007). Here again an economic balance must be struck between an occasional interruption of service, on the one hand, and the costs of larger drainage structures, on the other. Hydrology can provide the maximum design flow in order to get the minimum vent sizes for such

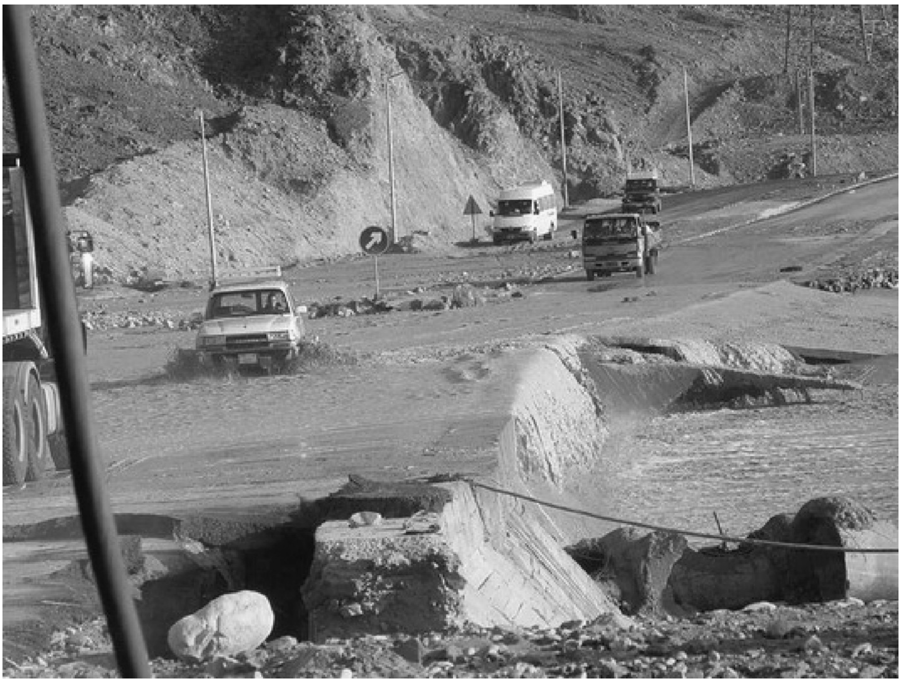

FIGURE 1.1 Flash flood damage to one of the highways crossing a stream at the Wadi Watir Sinai catchment, Egypt. (Adapted from Egyptian Water Resources Research Institute [WRRI]. 2005–2006. Report prepared for the Development of Wadi Watir in Sinai, Egypt to the Egyptian Ministry of Water Resources and Irrigation.)

structures, while hydraulics principles provide the basis for analyzing the effect of the structures on the flow beside the hydraulic design of the structure size and its protection needed.

Closely akin to the problem of highway and railroad culvert design are those of storm sewer design, though the hydrology of urban areas is a study in itself and is much more complex than the apparent similarity of such areas would suggest.

In any type of reservoir, provisions must be made for passing flood flows over or around the dam. The spillway structure is often the most expensive portion of the dam, and hence, it should be as small as possible. On the other hand, overtopping of the nonoverflow section is a serious matter, and in an earth dam it is almost certain to cause failure, with destruction and frequently death in the areas downstream. The best hydrologic design is a prerequisite to safe and economical dam design. The hydrologist must evaluate not only the probability of floods of various magnitudes but also the effect of the reservoir upon the distribution of the flood volume. This latter point is worthy of emphasis, because it is sometimes overlooked and unnecessary expenditures may be made on "overdesigned" structures to protect a dam on it from being overtopped, because of the pond action of the reservoir behind the dam.

The reader should note the distinction between hydrologic designs and hydraulic designs (Chow et al. 1988). The hydrologic design determines the quantity of water that must be handled, whereas the hydraulic design proceeds from there and determines the structure best suited for the job. The engineer is no more warranted in undertaking the hydraulic design of a structure without considering the hydrologic design than he or she would be trying to determine the size of the structural members without first ascertaining the load that may come upon them.

1.2.2 Municipal Water Supplies

Even in regions where water is in the most abundant supply, the location and development of sources adequate to the needs of urban and rural areas (Figure 1.2) and industries is a matter of increasing concern. Most laymen do not realize, and some engineers fail to appreciate, that the availability of water is often the limiting factor in the growth of municipalities.

Drought is another problem. First, hydrologists should recognize that the drought is less severe in some areas than in other "meteorologically similar" areas—in other words, a drought of the same overall intensity and probability of occurrence could, "next time," hit many catchments in arid regions harder than they were hit before. Next, hydrologists have at their disposal plenty of geological and botanical evidence that nature has come far from doing her worst in the dry years. Finally, hydrologists know that in many areas the increased pumping rates in certain years may already have lowered groundwater levels to the point that an even less severe drought might set new minima in stream flow and underground water reserves. Application of this knowledge in a specific case and producing a reliable quantitative answer is one of the most complex and important problems of hydrology.

FIGURE 1.2 Dam constructed across one of the streams of Sinai, Egypt. Notice the flood water that covers a farm and a road downstream. (Adapted from Egyptian Water Resources Research Institute [WRRI]. 2005–2006. Report prepared for the Development of Wadi Watir in Sinai, Egypt to the Egyptian Ministry of Water Resources and Irrigation.)

1.2.3 Irrigation

The hydrologic problems in irrigation are similar to those in water supply but occur on a bigger scale and particularly in arid and semi-arid regions. A few years ago, the hydrology of irrigation was relatively simple. Today, an equally summary analysis may still be adequate in some regions, however, we increasingly find ourselves confronted with limiting conditions and the complexities of the problem correspondingly increase. In some streams, appropriations of water far exceed the total discharge, and the downstream projects depend on "return flow" from upstream projects. Elsewhere, irrigation projects depend on groundwater reservoirs, artificially recharged by "water spreading" on permeable areas, and an elaborate system of hydrologic bookkeeping is required to keep inventory of the supply and determine safe pumping rates (Soliman 1990). A hydrologist is often called upon to evaluate new projects in areas where the margin of safety is already low, to discover new water sources for projects having difficulty, or to develop more economical methods of water use.

In most arid and semi-arid regions, the economy is founded largely upon irrigation, the raising of camels and sheep, and some limited industry. The continued security and development of this entire region will be increasingly dependent on the vision and skills of hydrologists.

1.2.4 Flood Control

The flood-control methods in arid and semi-arid regions include using reservoirs to hold back flash flood waters (Figure 1.3), channel improvements to speed them on their way, and diversions to transfer them to channels not available to them in nature (WRRI 2005–2006). Flood-control projects range from small improvements, such as localized dredging or channel straightening undertaken by municipalities, to large, basin-wide developments involving tens of millions of dollars.

The design of any flood-control project must be based on reliable hydrologic studies. First, the probable frequency of floods of various magnitudes must be statistically analyzed so that potential future flood losses may be reasonably predicted. Next, a "design flood" must be synthesized, and a variety of preliminary plans must be prepared for works that might protect against it. Then, a number of the more promising alternatives must be studied in detail, analytically, by means of hydrologic models, or by a combination of both. Flood-control studies are complicated by the

FIGURE 1.3 Detention dam constructed across one of the streams at Wadi Watir (Sinai, Egypt) as a flood control project. (Adapted from Egyptian Water Resources Research Institute [WRRI]. 2005–2006. Report prepared for the Development of Wadi Watir in Sinai, Egypt to the Egyptian Ministry of Water Resources and Irrigation.)

fact that they modify the natural regimen of the stream and thus, in the process of protecting one area, may increase flood damage in another. As a final step, the best alternatives must be investigated even more intensively, with an objective of seeing how they can be expected to behave when subjected to floods other than the design flood. Some types of works, for example, will give complete protection against floods smaller than the design flood, while others may not go into effective action on any flood except a major one. Again, some types of works are capable of withstanding floods greater than the design flood and even giving some protection against them, whereas with other types the occurrence of a super design flood can be expected to result in major damage to the works, complete loss of benefits, and possible additional losses.

Continued development of both the basic theory and the technique of flood-routing studies are essential to intelligent, economical planning of flood-control projects. Methods of study that were adequate in the day of the "local" project do not suffice for the integrated, basin-wide improvements toward which engineering and political thought are increasingly turning.

Flood forecasts are similar to flood control. During high water, we rely upon these forecasts for planning evacuations of threatened areas, organizing standby crews for emergency work on railroads and highways, and putting emergency controls into effect at municipal water plants and other public utilities. These forecasts, which have a remarkably high degree of accuracy, are the joint work of hydrologists and meteorologists.

1.2.5 Erosion Control

Soil is an exhaustible resource and provides the impetus for intensive study and the development of soil conservation practices in arid and semi-arid regions. Despite—or perhaps because of—the aggressive political and economic arguments that accompanied such developments, a sound foundation for truly scientific conservation practices rapidly evolved. In this development, the hydrologists, ecologists, and agronomists worked hand in hand.

From the standpoint of hydrology, erosion control problems center around the phenomena of overland flow and infiltration. How effective is a given cover of vegetation in protecting a soil from erosion? With given soil and given cover on a given slope, what is the critical distance from the crest beyond which erosion may be expected to begin? Under given initial conditions of soil and cover, at what rate of rainfall will surface runoff begin? How will the infiltration rate vary as rain continues? How many tons of soil will be lost per acre per year with various crops and cropping procedures? What effects will land conservation practices have on flood flows and low-water flows of streams? What types of structure are best suited for preventing erosion in ditches and arresting the development of gullies?

Loss of topsoil to streams means a deposition of that soil in other areas (Figure 1.4). In a natural state, a rough longtime balance of values may exist between the loss and gain; we need only consider the building up of alluvial plains and delta lands to see this. However, where there are existing farms, reservoirs, or canalized reaches, deposition of sediment is as much an economic loss as erosion, and the

FIGURE 1.4 Silt deposition upstream: a storage dam at one of the streams in Sinai, Egypt, during a low water level. Notice the high water level mark at the upstream face of the dam. (Adapted from Egyptian Water Resources Research Institute [WRRI]. 2005–2006. Report prepared for the Development of Wadi Watir in Sinai, Egypt to the Egyptian Ministry of Water Resources and Irrigation.)

loss from the topsoil of a headwater farm is not offset economically by the deposition in river bottoms or in the delta. Every dam creates a settling basin, in which the stream that has been momentarily brought to a halt drops its suspended load. Thus, the life of a reservoir is fixed, to a great extent, by the rate at which erosion is taking place in the tributary drainage area. Estimation of this “useful life” has become an important phase of the hydrologic investigation of proposed reservoir projects, but much work remains to be done both in establishing a sound analytical basis for such estimates and in developing procedures for the desilting of existing reservoirs whose life is threatened. A fascinating corollary of the reservoir-silting problem is the effect of clear water on the channel downstream. For every velocity and depth of flow, a river has a certain capacity for carrying suspended matter, and when robbed of its load by a reservoir, it tends to pick up a new charge of sediment from its bed and banks after leaving the pool. This may result in a lowering of the bed, radical changes in channel alignment, and steepening of the slopes of tributaries—in short, a complete upset of the physiographic balance that must either work itself out or be arrested by additional control works. Analysis of such problems is still in its infancy and is a stimulating challenge to the combined efforts of hydrologists and geologists.

1.2.6 Environmental Impacts

The growth of urban areas in arid and semi-arid regions has seen many environmental impacts on public health problems, not the least important of which is the pollution of streams. Many streams flowing downstream from cities have become open sewers, dangerous to public health, and destructive to wildlife and natural beauty. In less serious instances, stream pollution creates public nuisance. Table 1.1 provides classes of contaminants that are found in many streams. Pollution control is largely a sanitary engineering problem to be solved by the enforcement of strict laws, and involves vast expenditures of public funds for sewage and industrial waste treatment. The disposal of a certain amount of sewage by dilution is usually considered permissible, particularly after the second treatment, functioning through bacterial action and aeration. Complete prevention of stream pollution, although possible in some streams, is not economically feasible. It is here that the hydrologist can assist the sanitary engineer. A complete stream pollution control study must include an investigation of stream flow, particularly the magnitude and duration of low flows. In some instances, the augmentation of low flows by means of reservoirs has proved to be at least as important to the control of stream pollution as investments in additional sewage treatment plants.

1.3 HYDROLOGIC CYCLE

The hydrologic cycle deals with the movement of water, in its three phases—gas, liquid, and solid—from the ocean, land, or forests into the atmosphere by evaporation and transpiration. It passes through complicated atmospheric phenomena, generalized as the precipitation process, back to the earth's surface, upon and within which it moves in a variety of ways, and is incorporated into nearly all compounds and organisms. The relevant sciences that deal with the hydrologic cycle are astronomy, solar physics, cloud physics, meteorology, climatology, hydrometeorology, environmental sciences, geography, engineering, agriculture–biology, economics, surface

TABLE 1.1
Classes of Water Contaminants

Contaminant Class	Example
Oxygen-demanding wastes	Plant and animal materials
Infectious agents affecting plants	Bacteria and viruses
Nutrients	
Organic chemicals	Fertilizers such as nitrates and phosphates
Inorganic chemicals	Pesticides, detergent molecules
	Acids from coal mine drainage, inorganic chemicals
Sediment from land erosion	Clay silt on streambed
Radioactive substances	Waste products from mining and processing of radioactive material, radioactive isotopes after use
Heat from industry	Cooling water used in steam generation of electricity

water hydrology, limnology, oceanography, soil physics, ground water hydrology, and geology.

The hydrologic cycle, as given in Figure 1.5 (Soliman 2008), starts with the evaporation of water from the oceans by solar energy. The evaporated water (i.e., water vapor) rises by convection, condenses in the atmosphere to form clouds, and precipitates onto land and ocean surfaces, predominantly as rain or snow. Precipitation on land surfaces is partially intercepted by surface vegetation, partially stored in surface depressions, partially infiltrated into the ground, and partially flows over land into drainage channels and streams that ultimately lead back to the sea. Precipitation that is intercepted by surface vegetation eventually evaporates into the atmosphere; water held in surface depressions either evaporates or filters into the ground; and water that filters into the ground contributes to the recharge of groundwater, which either is utilized by plants or becomes subsurface flow that ultimately emerges as recharge to streams or directly to the ocean. Groundwater is defined as the water below the land surface; water above the land surface (in liquid form) is called surface water. The ground surface in urban areas is typically much less pervious than in rural areas, and surface runoff is mostly controlled by constructing drainage systems. Surface water and groundwater in urban areas also tend to be significantly influenced by the water supply and wastewater removal systems that are an integral part of urban development. Since human-made systems are part of the hydrologic cycle, hydrologic engineers must ensure that systems constructed for water use and control are in harmony with the needs of the natural environment in arid and semi-arid regions.

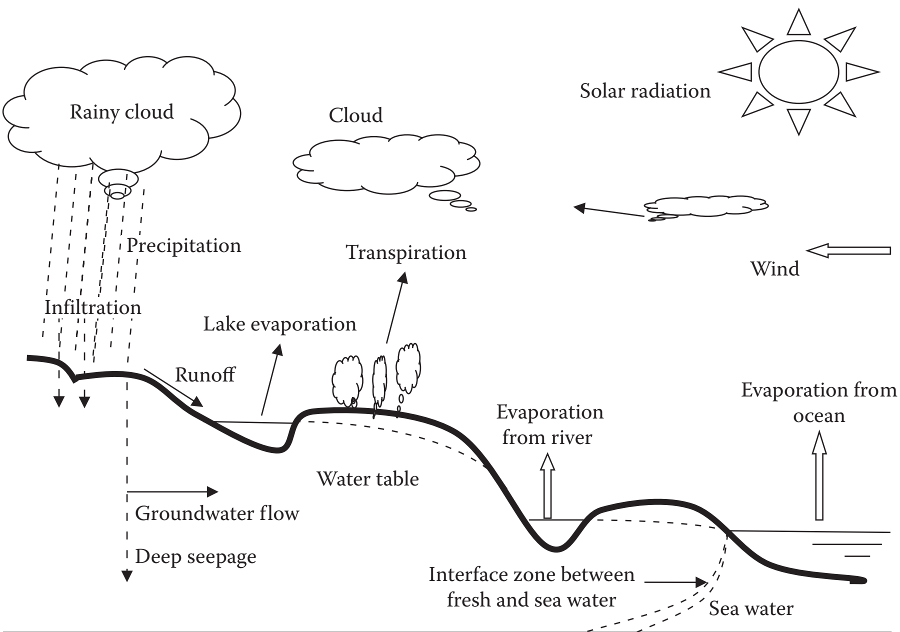

FIGURE 1.5 The hydrologic cycle.

The quality of water varies considerably as it moves through the hydrologic cycle, with contamination resulting from several sources. Classes of common contaminants were stated before in Section 1.2.6. The effects of the quantity and quality of water on the health of terrestrial ecosystems and the value of these ecosystems in the hydrologic cycle are often overlooked.

1.4 HYDROLOGIC SYSTEMS

Chow et al. (1988) defined the hydrologic system as a volume domain in space, surrounded by a boundary that accepts water and other inputs, operates on them internally, and produces them as outputs. The domain (for surface or subsurface flow) or volume in space (for atmospheric moisture flow) is the totality of the flow paths through which the water may pass from the point it enters the system to the point it leaves. The boundary is a continuous surface defined in three dimensions enclosing the volume. A working medium enters the system as input, interacts with the domain and other media, and leaves as output. Physical, chemical, and biological processes operate on the working media within the system; the most common working media involved in the hydrologic analysis are water, air, and heat energy.

The global hydrologic cycle can be represented as a system containing three subsystems: the atmospheric water system, the surface water system, and the subsurface water system (Figure 1.6). Another example is the storm–rainfall–runoff process on a watershed, which can be represented as a hydrologic system. The input is rainfall distributed in time and space over the watershed, and the output is stream flow at the

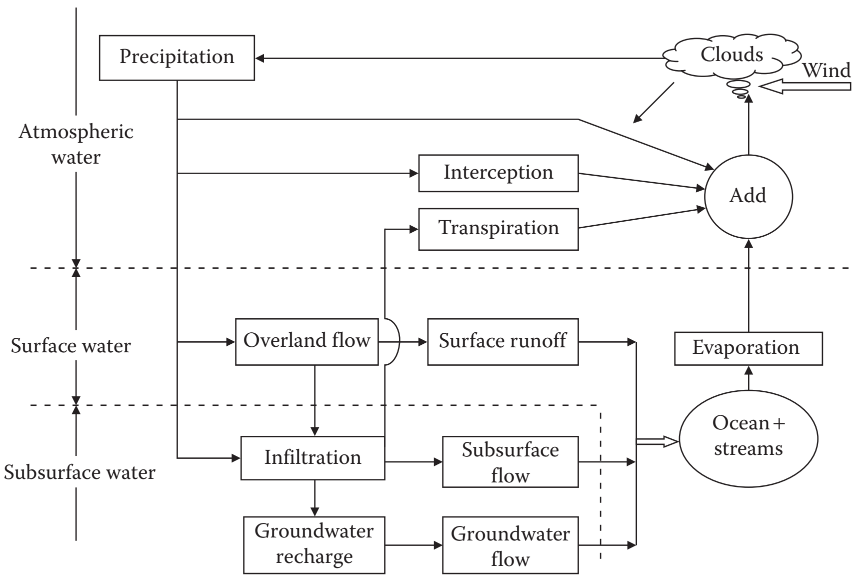

FIGURE 1.6 Block diagram showing the hydrologic system. (Adapted from Chow, V. T. et al. 1988. *Applied Hydrology*. New York: McGraw-Hill.)

watershed outlet. The boundary is defined by the watershed divide, and it extends vertically upward and downward to the horizontal planes.

The science that deals with the atmospheric water system is meteorology, more specifically hydrometeorology. The components of the hydrologic cycle, including the engineering aspects, will be discussed in this book, with enough information to perform water resources management in arid and semi-arid regions.

1.5 WADI HYDROLOGY

Although "wadi" is the name given to seasonal watercourses in the Arab region, it has been increasingly recognized as an international name used in most hydrologic publications all over the world. Yet, despite their great role as vital water supply sources and causes of catastrophic floods in many Arab countries, the scientific understanding and knowledge base of their hydrologic processes are rather poorly understood in most of these countries.

In recognition of this lack of understanding, the fifth cycle of the International Hydrological Program (IHP-V) of UNESCO (UNESCO 1996, 2002) gave great consideration to this topic in many of its eight themes. For example, seasonal watercourses have been explicitly included in various projects related to the theme "Integrated Water Resources Management in Arid and Semi-Arid Zones" (theme 5), while many of its components fit very well, among others, with projects related to the theme "Groundwater Resources at Risk" (theme 3) and "Knowledge, Information, and Technology" (theme 8). It is therefore logical that the above three themes have also been selected as priority areas for the region by the participants of the Sixth Regional Meeting of the IHP committees of Arab Countries, held in Jordan in December 1995. During the same meeting, wadi hydrology was specifically outlined as a target project. Both this project and the regional priority themes coincide with concentration areas of the UNESCO Cairo Office, that is, rainfall water management and groundwater protection. The author of this book, as a member of the Egyptian National Committee of IHP, was the first to suggest that wadi hydrology be used as a general term the hydrology of arid and semi-arid regions. This term may be applied to the catchments that are typically referred to as small drainage basins, but no specific area limits have been established. Wadi hydrology may also include the hydrologic studies of the coastal streams along both the Mediterranean Sea and the Red Sea in addition to the inland streams of arid and semi-arid regions. Figure 1.7 shows the streams' patterns at a coastal area near the city of Mersa Matruh on the north coast of Egypt. The stream catchments at this coastal area look almost the same. Figure 1.8 shows one of the catchments (Wadi Naghamish) at the coastal area of the Mediterranean Sea north of Egypt.

Because of the similarity of the coastal catchments' characteristics—rainfall and water management practices on the Mediterranean coast—the author of this book may suggest another term, "coastal hydrology," be applied to the wadis of the Mediterranean coast. Rainfall harvesting by the old Roman wells, galleries, and check dams across the wadis on the Mediterranean coast are still in use. Chapter 12 includes two cases of studies for rainfall harvesting in different arid and semi-arid coastal regions.

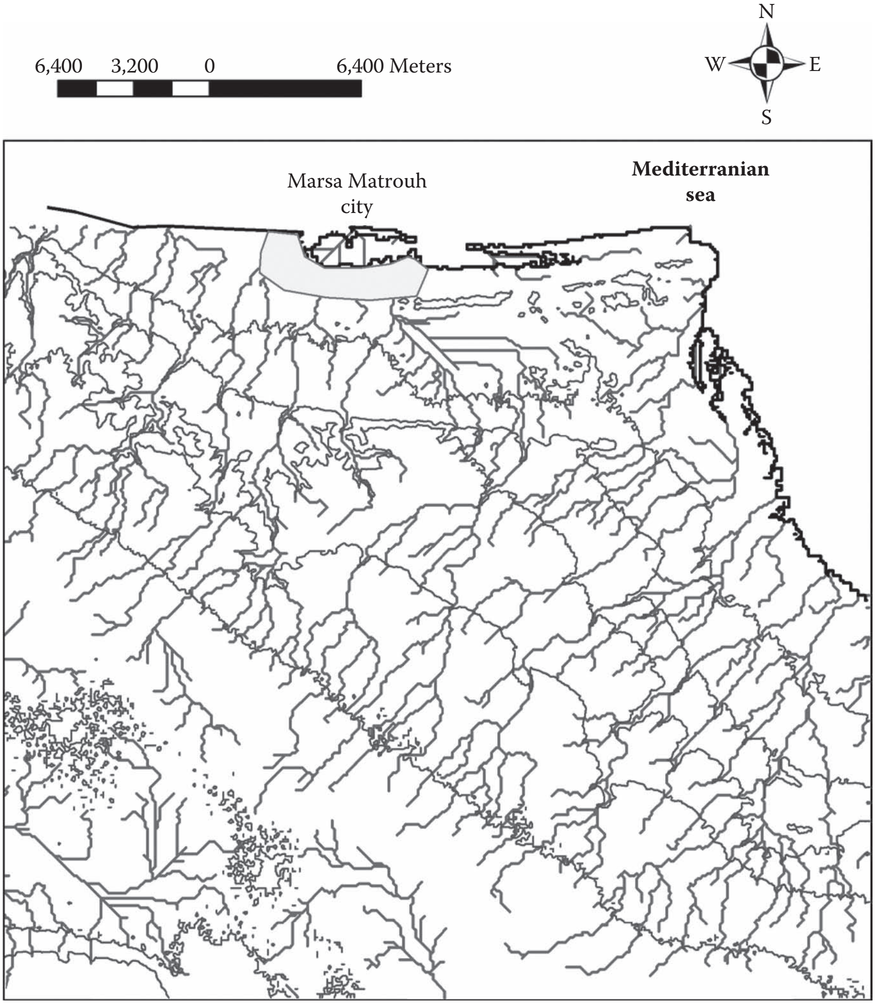

FIGURE 1.7 Stream distribution in the Mersa Matrouh area.

1.6 MODELING

Hydrologic models have been developed by a wide range of researchers and engineers for the management of surface and groundwater quantity and quality. Although these models have proven to be highly effective management tools, they have focused almost entirely on physical processes with little consideration of ecological dynamics. It is generally assume that plant communities have negligible impacts on hydrologic dynamics, but this is not the case in many terrestrial, riparian, and wetland systems. For example, brush invasion in many parts of the world was thought to have resulted in significant reductions in flow in streams and rivers. Expensive control programs have been widely implemented with little insight into long-term cost-effectiveness.

FIGURE 1.8 Wadi Naghamish.

Assessments of the impact of hydrologic alteration on vegetation and of vegetation on water supply can be greatly facilitated by linking existing hydrologic models with general ecosystem models designed to make long-term projections of ecosystem dynamics.

In arid and semi-arid regions, several surface and groundwater models have been applied with a considerable degree of success as long as the data needed for any catchment has been simulated and processed properly. This means that the results of the model should be verified with the observed values in order to obtain dependable results for flood forecasting or groundwater management.

The surface hydrologic modeling system is designed to simulate the rainfall–runoff processes of watershed systems. Its design is applicable to a wide range of geographic areas for solving diverse problems including large river basin water supply and flood hydrology and small urban or natural watershed runoff. A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed of interest. In most cases, several model choices are available for representing each water pathway in the cycle. Each mathematical model included in the program is suitable in different environments and under different conditions. Making the correct choice requires knowledge of the watershed and the goals of the hydrologic study and engineering judgment. The model features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. The following popular software models can be downloaded free through the Internet, from different sources:

1. WMS 7 Environmental Modeling System Incorporated (www.ems-i.com)
2. HEC-HMS by the Hydrologic Engineering Center
3. Hydrocad model (www.hydrocad.net)
4. Mod-flow (older version) for groundwater flow modeling
5. Simplified model of surface water hydrology and a groundwater model designed by the author, included at the end of this book

Of course, there are more hydrologic model software designed by researchers and institutes around the world. Users should select the models that suit their problems and their budget. Geographic information systems (GIS), together with Arc Hydro, helps a lot in organizing hydrologic databases by base map preparation, land use, soil type, drainage map, and contour map, needed for any hydrologic model.

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Hydrologic Models

Hydrological Model and Forecasting System (WATFLOOD)
Hydrologic Modeling System (HEC-HMS)
Hydrologic Simulation Model (HSIMHYD)
Illinois Hydrodynamic Watershed Model III (IHW-III)
Illinois Urban Catchment Runoff Simulation (ILUCAT)
Illinois Urban Storm Runoff Model (IUSR)
Integrated Hydro Meteorological Model (IHMM)

Interactive River-Aquifer Simulation Program (IRAS)
MIKE 11 RR (Rainfall Runoff)
MIKE SWMM
Rainfall-Runoff Modelling Toolbox (RRMT) and Monte Carlo Analysis Toolbox (MCAT)
Soil Conservation Service Curve Number Model (SCS-CN)
Storm Water Management Model (SWMM)

2 Meteorological Processes and Hydrology

2.1 INTRODUCTION

The hydrologic characteristics of an arid or semi-arid region are determined largely by its climate, geology, and geography. The climatic factors that establish the hydrologic features of these regions include the amount and distribution of precipitation and the effects of wind, temperature, and humidity on evaporation and evapotranspiration. Meteorology plays an important role in hydrologic problems such as determining probable maximum precipitation conditions for spillway design, forecasting precipitation for reservoir operation, and determining probable maximum winds over water surfaces (used for evaluating the resulting waves in connection with the design of dams and levees). Obviously, a hydrologist should have some understanding of the meteorological processes that determine a regional climate. The general features of climatology and climate change are discussed in this chapter.

2.2 SOLAR AND EARTH RADIATION

Solar radiation, the earth's chief energy source, determines the world's weather and climates. Both the earth and the sun radiate essentially as blackbodies; that is, for every wavelength they emit almost the theoretical maximum amount of radiation for their temperatures.

Radiation wavelengths are usually given in micrometers (μm; 10^{-6} m) or in angstroms (Å; 10^{-10} m). The maximum energy of solar radiation is in the visible range of 0.4–0.71 μm, and that of earth radiation is about 10 μm. Radiation from the sun is called shortwave radiation and that from the earth is called long wave radiation.

The rate at which solar radiation reaches the upper limits of the earth's atmosphere on a surface normal to the incident radiation and at the earth's mean distance from the sun is called the solar constant (Anderson and Baker 1967). Measurements of the solar constant range from 1.89–2.05 Langleys per minute (Langley is abbreviated Ly; 1 Ly = 1 calorie per square centimeter); most of the uncertainty in the measurement values results from corrections for atmospheric effects rather than from fluctuations in solar activity, which are considered relatively small. High-altitude observations with airborne instruments, which minimize atmospheric effects, indicate a range of 1.91–1.95 Langleys per minute, and 1.94 Langleys per minute is often used as the solar constant.

A large part of the solar radiation reaching the outer limits of the atmosphere is scattered and absorbed into the atmosphere or reflected from clouds and the earth's surface. The scattering of radiation by air molecules is most effective for the shortest wavelengths. With the sun over head and a clear sky, more than 50% of the radiation in the blue range (short wavelengths about 0.45 μm) is scattered, thus accounting for the blue sky. Very little radiation in the red range (about 0.65 μm) is scattered. Estimates of the amount of radiation scattered to space average about 8% of the incident solar radiation. Clouds reflect much incident solar radiation to space; the amount reflected depends on the amount and type of clouds and their reflectivity.

In general, good emitters of radiation are also good absorbers of radiation at specific wavelength bands; this is especially true of gases. This phenomenon is responsible for the earth's greenhouse effect. Likewise, weak emitters of radiation are also weak absorbers of radiation at specific wavelength bands. This is referred to as Kirchhoff's law. Some objects in nature can almost completely absorb and emit radiation and are called blackbodies. The radiation characteristics of the sun and the earth are very close to that of black bodies.

Wien's law states that the wavelength of maximum emission of any body is inversely proportional to its absolute temperature. Thus, the higher the temperature, the shorter the wavelength of maximum emission. The following equation describes this law:

$$\lambda \max = \frac{C}{T}$$

where C is a constant equal to 2897 μm*K and T is temperature in kelvin (Pidwirny et al. 2008).

According to this equation, the wavelength of maximum emission for the sun (5800 K) is approximately 0.7 μm, whereas the wavelength of maximum emission for the earth (288 K) is approximately 10 μm.

2.3 TEMPERATURE

2.3.1 Measurement of Temperature

To measure the air temperature properly, thermometers must be placed where air circulation is relatively unobstructed, and they must be protected from direct sun rays and from precipitation. The U.S. National Weather Service recommendation, which has been adopted by many countries, is that thermometers be placed in white, louvered, wooden instrument shelters through which the air can move readily. For better performance, the shelters should be set at about 1.4 meters above the ground. Many kinds of thermometers are available; however, the satellite remote sensing is the most up-to-date technique used to get the Vertical Temperature Profile Radiometer data (Shi et al. 2008).

2.3.2 Terminology

The terms "average," "mean," and "normal" are the same as arithmetic means. The first two are used interchangeably, but the term "normal," which is generally used as a standard of comparison, is the average value for a particular date, month, season, or year over a specific 30-year period (WMO 1967). Plans call for recomputing the

30-year normal every decade, dropping off the first 10 years and adding the most recent 10 years.

The mean daily temperature may be computed by several methods (WMO 1960). The most accurate practical method is to average hourly temperatures. Accurate results can be obtained by averaging 3- or 6-hour observations, although the random error for an individual day with irregular variations may be of some importance, especially for 6-hour observations. In some countries, climatological observations are made at selected hours (usually three per day: morning, noon, and evening) to permit computation of acceptable daily means by a formula that gives the mean as a linear function of the observed values, with constants depending on observation time, time of year, and location.

In the United States, the mean daily temperature is the average of the daily maximum and minimum temperatures and is usually less than a degree above the true daily average. Once-daily temperature observations are usually made at 7 AM or 5 PM. Temperatures are published according to the date of the reading, even though the maximum or minimum may have occurred on the preceding day. Mean temperatures computed from evening readings tend to be slightly higher than those from midnight readings. Morning readings yield mean temperatures with a negative bias; the difference is less than the evening readings. The maximum effect of arbitrary changes in observation time on the mean temperature varies with place and season and may exceed 1.6°C (Mitchell 1958).

The normal daily temperature is the average daily mean temperature for a given date computed for a specific 30-year period. The daily temperature range is the difference between the highest and lowest temperatures recorded on a particular day. The mean monthly temperature is the average of the mean monthly maximum and minimum temperatures. The mean annual temperature is the average of the monthly means for the year. The degree day is a departure of one degree for one day in the mean daily temperature from a specified base temperature.

The lapse rate, or vertical temperature gradient, is the rate of temperature change with height in the free atmosphere. The mean lapse rate is a decrease of about 1°C per 150 meters in the vertical direction. The greatest variations in lapse rate are found in the layer of air just above the land surface. The earth radiates heat energy to space at a relatively constant rate, which is a function of its absolute temperature in kelvin. At night, incoming radiation is less than the outgoing radiation, and the temperature of the earth's surface and the air immediately above the surface decreases. For more details, refer to the references. Global warming and cooling and their effects on the precipitation of arid and semi-arid regions will be discussed in Section 2.6.

2.4 HUMIDITY

2.4.1 Properties of Water Vapor

The process by which liquid water is converted into vapor is called evaporation. Water molecules with sufficient kinetic energy to overcome the attractive forces that tend to hold them within the body of liquid water are projected through the water surface. Because kinetic energy increases and surface tension decreases as temperature rises, the evaporation rate increases with temperature. Most atmospheric vapor is the product of evaporation from water surfaces. Molecules may leave a snow or ice surface in the same manner as they leave a liquid. The process by which a solid is transformed directly into a vapor state, and vice versa, is called sublimation. In a mixture of gases, each gas exerts a partial pressure independent of the other gases. The partial pressure exerted by water vapor is called vapor pressure. If all the water vapor in a closed container filled with moist air with an initial total pressure p were removed, the final pressure of the dry air alone would be less than p_d. The vapor pressure e would be the difference between the pressure of the moist air and that of the dry air $(p - p_d)$.

Practically speaking, the maximum amount of water vapor that can exist in any given space is a function of temperature and is independent of the coexistence of other gases. When the maximum amount of water vapor for a given temperature is contained in a given space, the space is said to be saturated. The more common expression “the air is saturated” is not strictly correct. The pressure exerted by the vapor in a saturated space is called the saturation vapor pressure, which, for all practical purposes, is the maximum vapor pressure possible at a given temperature.

Condensation is the process by which the vapor changes to the liquid or solid state. In a space in contact with a water surface, condensation and vaporization always occur simultaneously. If the space is not saturated, the vaporization rate will exceed the condensation rate, resulting in a net evaporation. If the space is saturated, the vaporization and condensation rates balance, provided that the water and air temperatures are the same.

Vaporization removes heat from the liquid being vaporized, whereas condensation adds heat. The latent heat of vaporization is the amount of heat absorbed by a unit mass of a substance, without a change in temperature, while passing from the liquid to the vapor state. The change from the vapor to the liquid state releases an equivalent amount of heat.

The latent heat of fusion for water is the amount of heat required to convert one gram of ice to liquid water at the same temperature. When one gram of liquid water at 0°C freezes into ice at the same temperature, the latent heat of fusion (79.7 calories per gram) is liberated.

The latent heat of sublimation for water is the amount of heat required to convert one gram of ice into vapor at the same temperature without passing through the intermediate liquid state. It is equal to the sum of the latent heat of vaporization and the latent heat of fusion, and at 0°C, it is about 677 calories per gram. Direct condensation of vapor into ice at the same temperature liberates an equivalent amount of heat.

The specific gravity of water vapor is 0.622 times that of dry air at the same temperature and pressure. The density of water vapor ρ_v in grams per cubic centimeter is

$$\rho_v = 0.662\left(\frac{e}{RT}\right) \tag{2.1}$$

where T is the absolute temperature in kelvin and R is the gas constant (2.87×10^3) cm/Kelvin when the vapor pressure e is in millibars. The density of dry air ρ_d in grams per cubic centimeter is

$$\rho_d = \frac{p_d}{RT} \tag{2.2}$$

where p_d is the pressure in millibars. Millibar is the standard unit of pressure in meteorology. It is equivalent to a force of 1000 dynes per square centimeter, 1 bar = 1000 millibars. The mean sea-level air pressure is 1013 millibars (see Appendix A).

The density of moist air is equal to the mass of water vapor plus the mass of dry air in a unit volume of the mixture. If p_a is the total pressure of the moist air, $p_a - e$ will be the partial pressure of the dry air alone. Adding Equations 2.1 and 2.2 and substituting $p_a - e$ for p_d gives

$$\rho_a = \left(\frac{p_a}{RT}\right)\left(1 - 0.378\left(\frac{e}{p_a}\right)\right) \tag{2.3}$$

This equation shows that moist air is lighter than dry air.

2.4.2 Terminology

2.4.2.1 Units

Many expressions are used to indicate the moisture content of the atmosphere. Each serves special purposes, but here we discuss only those expressions common to hydrologic uses. Vapor pressure (e), usually expressed in millibars but sometimes in millimeters of mercury, is the pressure exerted by the vapor molecules. In meteorology and hydrology, vapor pressure denotes the partial pressure of the water vapor in the atmosphere.

The saturation vapor pressure is the maximum vapor pressure in saturated space and is a function of temperature alone. At any given temperature below the freezing point, the saturation vapor pressure over liquid water is slightly greater than that over ice. Vapor pressure over water is generally used for most meteorological purposes, regardless of temperature. Table 2.1 gives the water properties and saturated vapor pressure values related to temperatures in Celsius.

2.4.2.2 Dew Point

The dew point (T_d) is the temperature at which space becomes saturated when air is cooled under constant pressure and with constant water vapor content. It is the temperature at which saturation vapor pressure (e_s) is equal to the existing vapor pressure (e).

2.4.2.3 Relative Humidity

The relative humidity (f) is the percentage ratio of the actual to the saturation vapor pressure and is therefore a ratio of the amount of moisture in a given space to the amount the space could contain if saturated.

$$f = 100\left(\frac{e}{e_s}\right) \tag{2.4}$$

TABLE 2.1
Properties of Water and Vapor Pressure in Metric Units

				Viscosity		Vapor Pressure		
Temperature (°C)	Specific Gravity	Density (g/cm^3)	Heat of Vaporization (cal/g)	Absolute (Centipoises)[b]	Kinematic (Centistokes)[c]	mm Hg	Millibars	g/cm^2
0	0.99987	0.99984	597.3	1.79	1.79	4.58	6.11	6.23
5	0.99999	0.99996	594.5	1.52	1.52	6.54	8.72	8.89
10	0.99973	0.99970	591.7	1.31	1.31	9.20	12.27	12.51
15	0.99913	0.99911	588.9	1.14	1.14	12.78	17.04	17.38
20	0.99824	0.99821	586.0	1.00	1.00	17.53	23.37	23.83
25	0.99708	0.99705	583.2	0.890	0.893	23.76	31.67	32.30
30	0.99568	0.99565	580.4	0.798	0.801	31.83	42.43	43.27
35	0.99407	0.99404	577.6	0.719	0.723	42.18	56.24	57.34
40	0.99225	0.99222	574.7	0.653	0.658	55.34	73.78	75.23
50	0.98807	0.98804	569.0	0.547	0.554	92.56	123.40	125.83
60	0.98323	0.98320	563.2	0.466	0.474	149.46	199.26	203.19
70	0.97780	0.97777	557.4	0.404	0.413	233.79	311.69	317.84
80	0.97182	0.97179	551.4	0.355	0.365	355.28	473.67	483.01
90	0.96534	0.96531	545.3	0.315	0.326	525.89	701.13	714.95
100	0.95839	0.95836	539.1	0.282	0.294	760.00	1013.25	1033.23

[a] Maximum density is 0.999973 g/cm^3 at 3.98°C.
[b] Centipoise: g/cm s 10^2.
[c] Centistokes: $cm^2/s \times 10^2$.

Relative humidity can also be computed directly from air temperature T and dew point T_d by an approximate formula that is convenient for computer use:

$$f = \left[\frac{(112 - 0.1T + T_d)}{(112 + 0.9T)} \right]^8 \tag{2.5}$$

where the temperature is in Celsius. This formula approximates relative humidity to be within 1.2% in the meteorological range of temperatures and humidity to be within 0.6% in the range of –25–45°C (–13–113°F).

2.4.3 Measurement of Humidity

In general, humidity (Stine 1965) in the surface layers of the atmosphere is measured with a psychrometer, which consists of two thermometers, one with its bulb covered by a jacket of clean muslin saturated with water. The thermometers are ventilated by whirling or a fan. Because of the cooling effect of evaporation, the moistened, or wet-bulb, thermometer reads lower than the dry thermometer. The difference is called the wet-bulb depression. The air and wet-bulb temperatures are used to obtain various expressions of humidity by reference to the psychrometric table provided in Table 2.2 (USA Weather Bureau 1972). Instruments such as hair hygrometers and dew point hygrometers can be used to measure humidity, but they give an appreciable error if they are not used in a proper manner. Fortunately, several electronic instruments that can accurately measure the relative humidity are available and can be easily ordered through the Internet.

2.5 WIND

Wind is a very influential factor in several hydrometeorological processes. Moisture and heat are readily transferred to and from air, which tends to adopt the thermal and moisture conditions of the surfaces with which it is in contact. Stagnant air in contact with a water surface eventually assumes the vapor pressure of the surface so that no evaporation takes place. Similarly, stagnant air over a snow or ice surface eventually assumes the temperature and vapor pressure of the surface so that melting by convection and condensation ceases. Consequently, wind exerts a considerable influence on evaporation and is also important in the production of precipitation, since precipitation can be maintained only through sustained inflow of moist air into a storm.

2.5.1 Measurement of Wind

Wind has both speed and direction. The wind direction is the direction from which it is blowing. For surface winds, direction is usually expressed in terms of 16 compass points (N, NNE, NE, ENE, etc.), and for winds aloft in degrees from the north, the direction is measured clockwise. Wind speed is usually given in miles per hour, meters per second, or knots (kn; 1 meter per second = 2.237 miles per hour = 1.944 knots; and 1 knot = 1.151 miles per hour = 0.514 meters per second).