1 THE HYDROLOGIC CYCLE

1.1 WATER

Water is the most common substance on earth, and yet it is a marvelous entity. Water covers over 70 percent of the earth's surface and participates in all of its processes. It is essential to life on the planet, making up a substantial proportion of every living organism. Water is the only substance on earth that is naturally present on all three phase forms: liquid, solid (ice), and gaseous (water vapor). At the molecular scale, water is composed of two hydrogen atoms sharing electrons with an oxygen atom (H_2O in chemistry notation). This causes an asymmetric distribution of electrons, a corresponding positive charge on one side of the molecule, and a negative one on the other. The polarity results in an electrostatic attraction between molecules and in unique properties affecting planetary processes.

Water possesses a high capacity to absorb heat, a fact that produces many interesting phenomena. The ability of water to absorb large amounts of heat permits solar energy to warm the oceans. This heat is subsequently transferred to the atmosphere. Because the earth's equator is tilted with respect to the plane of its orbit around the sun, seasonal variations in temperature occur. At the same time, the rotation, translation, and precessional movements of the earth create unequal heating on its surface, and differences in atmospheric pressure. Thus, winds, storms, and hurricanes are produced. At the same time, ocean currents warm lands in the northern hemisphere.

Water is a universal solvent. It is slightly acidic and thus dissolves many minerals in its path through the atmosphere, soils, and rivers. Since water is a carrier of substances and has the ability to chemically react with complex organic compounds, it constitutes an essential part of plant and animal nutrients; it actively participates in feeding, assimilation, and excretion processes of living organisms.

Water possesses a high surficial tension. This feature supports many physical and biological processes involving water in small spaces. Water is the only compound whose solid state is lighter than its liquid one. This causes ice to float on liquid water, and permits aquatic life to survive during the winter months. Water transparency permits solar radiation to reach various depths, which allows photosynthesis below the water surface.

1.2 THE NATURE OF HYDROLOGY

Hydrology is the earth science that studies the occurrence, distribution, movement, and properties of the waters of the earth. Hydrology describes and predicts the spatial and temporal variability of water in the terrestrial, oceanic, and atmospheric systems. Hydrology investigates the movement of water on and under the earth's land surfaces, the physical laws inherent to that movement, the transport of contaminant substances in water, and the intervening chemical and biological processes.

Origins and Evolution of Scientific Hydrology

Since the dawn of civilization, humans have depended on the availability of fresh water. Humans understood that water was a pre-requisite to life on the planet, it was essential to health, it affected the production of food, and it was a fundamental means of transportation. In addition, humans observed that water was associated with certain natural phenomena, such as floods and thunderstorms. For these reasons, humans learned to fear, to worship, and to attribute mystic powers to water. Water is part of most mythological and ancient religious traditions of all civilizations in the past.

Parallel to this symbolic representation of water was the necessity to understand and control the environment. Many civilizations in the past attempted to modify the natural distribution of water for their benefit, and in that process many basic facts and empirical laws were learned. For example, about 4000 B.C. a dam was constructed across the Nile to permit reclamation of previously barren lands for agricultural production. The Greeks and especially the Romans built impressive aqueducts that covered vast lands, some of which continued to operate until very recently (e.g., the Segovia aqueduct in Spain operated until the mid twentieth century). The Chinese irrigation and flood control works were also significant projects. The Incas in Peru developed sophisticated water distribution and irrigation systems that permitted the construction of large cities on the top of mountains.

It is suspected that the concept of the hydrologic cycle dates back to ancient Egypt. Preliminary concepts of mass conservation and the relationship between precipitation and streamflow were conceived by early Greek philosophers, such as Thales, Anaxagoras, Herodotus, Hippocrates, Plato and Aristotle. These concepts were based on philosophical analyses and not on physical observation. For this reason, the mechanism of the hydrologic cycle was conceived in a variety of imaginative ways. The theories of the Greek philosophers dominated until the Renaissance. In the mid sixteenth century Leonardo da Vinci in Italy and Bernard Palissy in France asserted, on the basis of field observations, that water in rivers comes from precipitation. In the seventeenth century Pierre Perrault and Edmé Mariotte in France published the first quantitative measurements that verified the rainfall origin of streamflow. Early in the eighteen century the English scientist Edmund Halley extended the quantifying of the hydrologic cycle by estimating the amounts of water involved in the ocean-atmosphere-rivers-ocean cycle of the Mediterranean Sea and surrounding areas.

In the eighteenth century the development of mathematical applications to fluid mechanics and hydraulics brought several important contributions by Europeans, such as Bernoulli, Chézy, Euler, Pitot and others. By about 1800 the modern concepts of evaporation and global hydrologic cycle were established by the English scientist John Dalton. Around that time routine network measurement of precipitation began in Europe, the United States, and India. In the mid nineteenth century the fundamental law of groundwater flow was formulated by the French engineer Henry Darcy. The same century saw many advances in fluid mechanics, hydraulics and sediment transport by Poiseuille, Dupuit, DuBoys, Stokes, Manning, Reynolds, and others whose names have become associated with particular laws or principles.

By the end of the nineteenth century treatises on various aspects of hydrology began to appear. Many of these works examined the relationship between rainfall and streamflow amounts, due to the need to estimate flood magnitudes for the design of bridges, and other structures. This was the beginning of a close association between hydrology and civil engineering, although hydrology has gradually evolved as an independent environmental science related to many other professional disciplines.

The twentieth century saw rapid developments in hydrologic science. With the formation of the Section of Scientific Hydrology in the International Union of Geodesy and Geophysics in 1922, the Hydrology Section in the American Geophysical Union in 1930, and the proliferation of many national and international organizations devoted to the advancement of hydrology, the field has been formally recognized as a scientific discipline. Many individuals have contributed to this rapid expansion of the hydrologic sciences: A. Hazen, E.J. Gumbel, H.E. Hurst, and W.B. Langbein in the applications of statistics to hydrology; O.E. Meinzer, C.V. Theis, C.S. Slichter, and M.K. Hubbert in the development of various concepts of groundwater mechanics; L Prandtl, T. Von Kármán, H. Rouse, V.T. Chow, G.K. Gilbert, and H.A. Einstein in stream hydraulics and sediment transport; R.E. Horton and L.B. Leopold in the development of fundamental knowledge of infiltration, runoff processes and quantitative geomorphology; W. Thornthwaite, and H.E., Penman in the understanding of climate and evapotranspiration; and A. Wolman and R.S. Garrels in the understanding and modeling of water quality.

The advent and rapid development of computer science has provided a unique opportunity to hydrologists involved in the analysis of vast and complex hydrologic data. In addition, computers have made possible the construction and testing of mathematical models representing the different elements of the hydrologic cycle, and their complex inter-relationship. Mathematical analyses and numerical algorithms have found fruitful applications in the simulation of natural hydrologic processes. These have generated not only intrinsic understanding of fundamental laws of hydrology, but also useful tools with practical predictive applications in several engineering design tasks.

For interesting accounts on the origins and evolution of the concept of the hydrologic cycle and the history of hydrology, see Biswas (1970) and Nace (1974). The twentieth century also saw the first discoveries on the relationship between hydrological, environmental, and climatic science. Pioneers like V. Schauberger enunciated basic principles about the health effects of thermal and chemical pollution of water; the consequences of deforestation, river regulation, energy production, and global warming; and the existence of undiscovered subtle energies in water (Bartholomew, 2005; Cobbald, 2006; Schauberger, 1998). Interesting descriptions on the role of hydrology in climate change and the hydrologic effects of global warming can be found in Botkin and Keller (2005).

The Importance of Hydrology

Even though water is the most common substance on earth, 99 percent of it is unsuitable for drinking and other uses. Nearly 97 percent of the earth's waters are in the oceans, and about 2 percent constitute ice caps and glaciers. Thus, the usable water for people, plants, and animals is less than 1 percent of the total. The remaining water resources are being overused or polluted, leading to a growing global water shortage. The increasing shortages are causing famine, economic disruption, and even war in some places. The global society of today is characterized by an intense exploitation of natural resources, and in particular, water resources. The dramatic increase in the world population, accompanied by the rapid industrial and technological development with emphasis on consumption, has placed an unprecedented demand on natural water systems. At the same time, development and construction projects, industrial production and distribution of materials and goods, and the disposal of waste is continuously threatening the quantity and quality of existing surface and subsurface water resources, with the corresponding adverse effects on natural ecosystems and human health. The level of complexity of today's society requires development plans that minimize the damage to natural environmental systems, and remedial actions to restore or counteract the results of poor management practices and accidents of the past.

Because water and environmental issues are inextricably linked, hydrology is a multi-disciplinary science of utmost importance to the environmental fields today. A knowledge of hydrology is fundamental to decision-making processes where water is a component in a system of concern. Hydrologic theory offers valuable tools to understand and quantify physical, chemical, and biological processes related to an engineering or natural system where water is an important player. Development and construction projects, restoration and reclamation activities, and environmental accidents require either an assessment of the effects on related water resources, or specific quantitative information for the purposes of engineering design. Thus, hydrology provides *a priori* or *a posteriori* qualitative or quantitative information that helps the engineer, resource or project manager, scientist, or government official make sound decisions.

Hydrology is an integral part of several disciplines, such as environmental engineering and environmental science, water resources engineering, hydraulic engineering, geotechnical engineering, transportation engineering, chemical engineering, mining engineering, agricultural engineering, agriculture, forestry, geography, geology, toxicology, and biology. Today's hydrologist works in one or more of the above disciplines. He investigates, quantifies, assesses, predicts, or designs for diverse projects where water is an important component. Hydrology provides the tools and the information needed in many applications in engineering analysis and design. Examples of applications are:

- Design of surface water reservoirs
- Design of groundwater reservoirs
- Design of urban storm water sewers and airport drainage systems
- Design of urban water distribution systems

- Design of dikes and other flood control structures
- Design of locks, ports, and other navigational systems
- Design of agricultural irrigation systems
- Design of agricultural drainage systems
- Design of temporary construction and mining drainage systems
- Design of tunnels and underground excavations
- Design of flow control systems for highway development
- Design of bridges and other river foundations
- Design of open channels and other river flow control structures
- Forecasting of flood waves propagation
- Design of soil conservation measures
- Design of sanitary landfills and waste disposal facilities
- Management of rivers, lakes, wetlands, estuaries, and aquifers
- Management of crops, forests, and pasture lands
- Prediction of contamination effects on rivers and lakes
- Prediction of contaminants propagation in soils and groundwaters
- Prediction of effects of drainage on flood flows
- Prediction of environmental impact of water resources projects
- Prediction of environmental impact of deforestation
- Prediction of environmental impact of urbanization
- Prediction of environmental impact of chemical spills
- Prediction of environmental impact of chemical leaks from tanks
- Prediction of environmental impact of leachates from landfills
- Prediction of environmental impact of pesticide application
- Prediction of environmental impact of global climate change
- Design of contaminated-soil remedial systems
- Design of polluted-aquifer containment or restoration systems
- Analysis of the effect of climate change on water resources

As can be seen, hydrologic science has many applications in various fields. It constitutes a discipline for the environmental professional of today. Clearly this book does not intend to cover the details of design procedures for the above applications, which are covered in specialized design texts. Instead, it is a comprehensive introduction to hydrologic science and engineering, and hydrologic analysis. Hydrology provides the qualitative and quantitative analytic tools, which will produce the necessary information for the above applications.

Hydrology is concerned with the identification and analysis of important variables related to a particular project. For example, hydrologic analysis provides the designer of a reservoir with appropriate mathematical models to estimate time distribution of evaporation. Hydrology will also offer objective methods to estimate the probable maximum precipitation in the area, mean streamflow rate and its time variability, emergency peak flow rate, groundwater flow contributions, and minimum flow rates. This information is later used by the engineer in the dimensioning (i.e., the design itself) of the hydraulic structures required, such as the dam location and height, emergency spill way, energy dissipation structures and delivery systems.

Consider the case of a regional groundwater system contaminated by a chemical spill. The hydrologist will be involved in the collection of contaminated water samples, the analysis and quantification of the groundwater flow velocity and direction, the study of regional recharge from rainfall and the areas of natural discharge, and the investigation of the possible paths the contaminant may propagate in the subsoil. The hydrologist will also use mathematical methods to predict the concentration of toxic contaminants at certain sensitive areas in the future. She will then compare these values with maximum permissible concentrations derived from health-risk considerations. Finally, the hydrologist will offer alternatives of containment or remediation and will participate in the design of the respective structures.

1.3 THE HYDROLOGIC CYCLE

As a science focusing on the circulation of water and other substances in the planet, hydrology studies different processes that affect this movement. These processes interact in a complex manner in a particular water-drainage area, called a watershed. The following is a list of the fundamental hydrologic processes:

Precipitation

The fundamental physical process of interest in hydrology is *precipitation* (P), its nature, its occurrence, its spatial distribution at a fixed time, and its time evolution at a fixed location.

Interception

Interception (I_n) is the retention of precipitated water by the vegetation and other forms of cover on the drainage area. This water is temporarily stored on the leaves and other surfaces, and then evaporates back to the atmosphere. Depending on the vegetation type and density, and on the season, interception may be an important variable in the hydrologic cycle of a watershed.

Depression Storage

Precipitation that has reached the ground surface may be temporarily stored in surface depressions. This process is called *depression storage* (I_d). This water may evaporate or infiltrate after the storm. Depending on the soil hydraulics, vegetation, and topography of the area, depression storage may affect the redistribution of water in the watershed.

Infiltration

Water penetration and redistribution in the soils is called *infiltration* (I). It constitutes one of the most important hydrologic processes affecting not only the partition of water between surface and subsurface components, but also the recharge of aquifers and the transport of contaminants through the subsurface.

Evaporation

Evaporation of water (E) is the change of phase, from liquid to vapor, and the subsequent transport of water from the oceans, lakes, rivers and soils to the atmosphere. Evaporation constitutes an important means of water loss. It depends on several meteorological factors and on the availability of water. Of interest in hydrology and hydrologic applications is the spatial and time distribution of evaporation.

Transpiration

Transpiration (T) is a form of evaporation occurring from the leaves of plants and trees. Transpiration depends on the plant biological processes, species, location, and soil moisture, as well as meteorological factors affecting evaporation.

Streamflow

Streamflow or river flow (Q) is the resultant of contributions from *surface* or *overland flow* (R_o), *subsurface* flow or *interflow* (Q_s), and *groundwater flow* (Q_g). Hydrology studies the relative importance of each of these components and the time distribution of streamflow. Many applications are centered on the analysis of streamflow in a particular watershed.

Flood Routing

Motivated by the need to predict the propagation of catastrophic flood waves through a river system, several techniques have been developed to mathematically simulate this phenomenon. These techniques are called *flood routing*.

Groundwater

Water moving through geologic formations is called *groundwater flow* (Q_g). Hydrology studies the occurrence of groundwater, its seasonal recharge behavior, the movement of water through aquifers, and the discharge of water into streams, lakes, and oceans. Because it controls the low levels in rivers and lakes, and constitutes one of the most important sources of fresh water, groundwater is one of the most studied areas of hydrology.

Snowmelt

The melting of precipitated snow and ice is an important component of the hydrologic cycle in cold climates. Depending on the snow pack characteristics and on the time distribution of air temperature, solar radiation and other variables, *snowmelt* may become an important source of infiltration and streamflow during the spring season.

Sediment Transport

Precipitation, surface runoff, and streamflow are hydrologic processes encouraging the detachment, transport, and deposition of solid particles. *Sediment transport* analysis is of interest to individuals involved in soil conservation in natural and agricultural areas, river channel stability, and reservoir design.

River Pollution

Hydrologic processes affecting streamflow are also important physical processes controlling the transport of contaminants through river systems. Many hydrologic applications today are centered on the prediction of the effect of certain contaminant load, or contaminant spill, on the water quality of a river. The water quality affects the ecology of a river and determines the possible health effects associated with human exposure. Thus hydrology studies the mixing, transport, chemical, and biological processes associated with water flow and contaminant movement in rivers.

Pollution in Lakes

Since lakes and wetlands possess distinct physical hydrologic conditions, lake water quality resulting from various pollution loads are governed by special processes of interest to hydrologists.

Soils and Groundwater Pollution

Water flowing through soils and groundwaters is capable of carrying contaminants resulting from natural dissolution processes, or from human-based contamination products originated from chemical spills, sanitary landfills, or agricultural activities. Modern hydrology investigates the physical, chemical, and biological processes that affect the dispersion of contaminants through the subsurface. There are many applications of hydrologic methods of contaminant propagation prediction to the assessment of contamination, waste containment, and aquifer restoration activities.

The basic mechanism of the global hydrologic cycle is illustrated in Figure 1.1, which represents a portion of the earth profile with some of the most important hydrologic processes. The fundamental driving force of the hydrologic cycle is the radiation from the sun (R). Solar radiation causes the evaporation (E) from the oceans, rivers, lakes, and the soil. The solar radiation also drives the transpiration (T) from the vegetation. The evaporation and transpiration increases the amount of water-vapor present in the air. Masses of air loaded with moisture tend to rise, since they are less dense than dry air. Atmospheric moisture is then subjected to lateral movement by the regional wind velocity (W), which is also the result of atmospheric pressure differences caused by unequal spatial distribution of solar radiation on earth. As the masses of moist air move upward and laterally, they may eventually cool down and begin to condensate to form clouds. When the energy conditions in the cloud are appropriate, water will begin to descend to the surface of the earth to form precipitation (P).

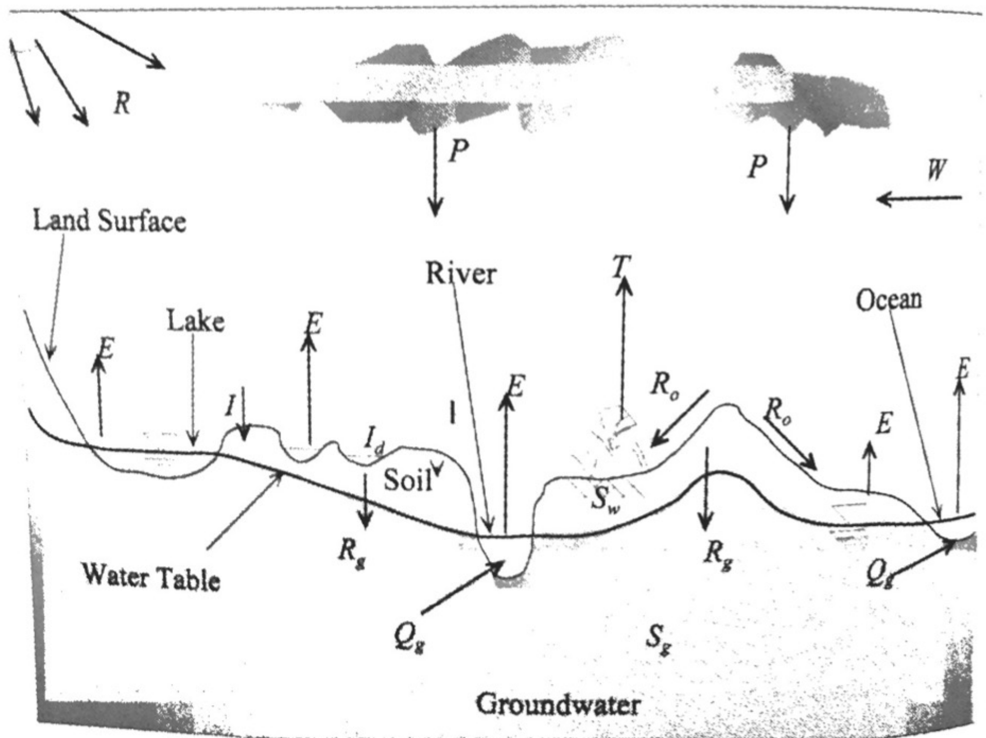

Figure 1.1: General Description of the Hydrologic Cycle

As precipitation approaches the surface of the earth, it is first retained by the leaves of the vegetation and other structures. The amount of water retained in this form is called interception (I_n). If it continues to rain, the excess of precipitation over interception will reach the ground surface and will immediately penetrate the soil via the process of infiltration (I). Infiltrated water will cause an increase in the amount of water present in the soil, called soil moisture or soil-water content (S_w). Water in the soil will move laterally, in the form of subsurface flow or interflow (Q_s), and downward vertically to eventually produce recharge (R_g) to the saturated zone or groundwater zone. Groundwater recharge will cause an increase in the amount of water present in the aquifer (or the groundwater reservoir), called groundwater storage (S_g). Groundwater will slowly move through the aquifer to eventually discharge into rivers, lakes, and the ocean (Q_g).

The excess of precipitation over interception and infiltration (i.e., precipitation that cannot infiltrate), will begin to pond over the ground surface to fill small ground surface depressions. This amount of water is called depression storage (I_d). If it continues to rain, the excess of precipitation over interception, infiltration, and depression storage will begin to flow as overland flow (R_o). Overland flow will eventually discharge into rivers, lakes, and the ocean. Thus, river flow, or streamflow, receives contributions from overland flow, subsurface flow, and groundwater flow. However, each of these contributions has a different proportion and a different arrival time, depending on the precipitation, the soil, the geology, the vegetation and other characteristics of the area.

The above description of the hydrologic cycle is general. Clearly, some of the mechanisms and pathways vary from place to place. For example, in an unforested area the interception might be negligible as compared to that in a forested one. In an urban watershed, the ground surface is practically impervious and the infiltration process might be negligible. On the other hand, a naturally forested area offers the ideal conditions where interception and infiltration are significant. Mountain or steeply sloping watersheds may be controlled by a significant amount of subsurface flow, as compared to overland flow and groundwater flow. Desert areas are characterized by low precipitation, low streamflow, and high evaporation. Karst geology, characterized by units of calcium and magnesium carbonate, offers unique conditions where turbulent groundwater flow coupled with negligible overland flow controls the hydrologic cycle of the area.

The hydrologist needs to investigate local climatic, geologic, topographic, and vegetative characteristics of the watershed in question to understand special conditions of the hydrologic cycle. Geological maps, precipitation data, air temperature data, topographic maps, aerial and satellite pictures are but a few of the available tools in this analysis. A conscientious study of the physical characteristics of a watershed of interest is essential to an understanding of the most important hydrologic processes in place, and to a subsequent quantification of the dominant variables.

Climate Variability and Hydrology

Hydrologists routinely study seasonal and annual fluctuations in precipitation and other weather variables. The repetitive nature and pattern of these fluctuations over a period of many years constitute the characteristic climate of a region. There is increasing evidence that the earth's water resources is undergoing a gradual change impacted by both multiple-year cycles in fluctuating weather patterns and graduate changes in the climate over spans of multiple decades. *El Niño Southern Oscillation* phenomenon is an example of fluctuations in global weather patterns that approximately occurs at cyclical multiple-year intervals. On the other hand, human-induced impacts on *global warming* associated with greenhouse gases is a long-term climate change problem receiving much attention in the scientific community (Lettenmaier, McCabe, and Stakhiv, 1996; National assessment Synthesis Team, 2000).

El Niño Southern Oscillation is the best known anomaly resulting from interactions between weather and oceanic systems. It is a quasicyclic phenomenon that has occurred every 3 to 7 years during the last 450 years (Wurbs and James, 2002). It refers to the abnormally high sea surface temperatures off the coast of Peru. The coastal land of Peru is covered by the Atacama desert, a dry region receiving very little rain. The nearby Pacific Ocean is a very productive fishery. However, El Niño years are marked by a disruption in the usually abundant supply of fish, and flooding rains may fall on the desert. This phenomenon is accompanied by low atmospheric pressure over the eastern Pacific and high atmospheric pressure over the western Pacific. El Niño is the result of large-scale, long-period, waves in the surface of the tropical Pacific Ocean. This produces temporary changes in winds and atmospheric moisture circulation, which cause unusual weather patterns in low and mid-latitude regions around the globe. Some regions may experience unusually warm or cold winters, severe droughts may occur in normally wet agricultural regions, while intense rains may fall over normally dry regions.

The earth's climate has undergone a slow but continuous change throughout its history. Warming and cooling cycles have occurred in the past, each lasting thousands of years. A highly debated issue in the scientific community is the possible effect of human activities on climate change. In particular, there is an ongoing discussion about the possible warming effect of increased concentrations of carbon dioxide and other trace gases in the atmosphere due to the burning of fossil fuels accompanied by increased deforestation of large areas. This topic is known colloquially as the greenhouse effect (Mimikou, 1995). As solar energy reaches the earth, some of it is reflected back, and some of it is absorbed. The outgoing infrared radiation is partially absorbed by clouds, carbon dioxide, water vapor, and other gases. This energy is then radiated in all directions, including back to the earth. The natural greenhouse effect is beneficial to earth because it regulates temperature, which would otherwise be too cold to sustain life. However, human activities now substantially increase the emission of greenhouse gases such as carbon dioxide and nitrous oxide from the burning of fossil fuels. Methane is also added to the atmosphere by agriculture and municipal landfills. Chlorofluorocarbons are released through various means, such as outdated air-conditioning coolants, plastic foams, and aerosol propellants. At the same time, the proportion of forests is substantially decreased. Plants have the natural ability to consume carbon dioxide and release oxygen. Thus, the natural balance of greenhouse gases existing prior to the industrial revolution has been disrupted.

Of interest to the hydrologist is the extent of the effect of global warming resulting from an increase in greenhouse gases on the characteristics of precipitation, soil moisture, surface and groundwater availability, droughts, and floods. Changes in the local hydrologic cycle are possible during the 21st century, and the consequences to water management may be substantial. While climate change occurs at the global scale, the effects of changes in state-atmospheric variables will be felt at the local watershed scales (English et al, 2005; Szép et al, 2005; Li et al, 2004; Laiho et al, 2004; Venugopal, et al 1999). To assess this possibility, previous studies have focused on the coupling of regional climate models with landscape-scale hydrologic models (e.g., Hostetler and Giorgi, 1993). There is a need for an alternate analysis of point precipitation, temperature, and solar radiation coupled with the nonlinear differential equations governing infiltration, soil moisture, deep recharge, and groundwater discharge.

There is evidence of increasing soil-surface temperature due to the complex interaction of increased air temperature and corresponding increased precipitation (Gosnold et al., 1997). Long-term variability in precipitation and air temperature regimes affect the corresponding evapotranspiration and energy balances at the soil surface and will result in possible long-term changes in the soil-moisture regime (Goyal, 2004). The impacts of these changes on the hydrochemical and stream flow regime may be dramatic (Avila et al., 1996). The state variables in the upper soil layers (e.g., the volumetric water content) control, not only vegetation cover and soil fauna (Chadwick, 2003; Tonkov, 2003; Sulkava, and Huhta, 2003), but also the transient variability in output recharge to regional aquifers (slow response) and output overland flow supply (fast response). There is some evidence of an important role of incoming solar radiation and inter-annual precipitation on the nonlinear response of aquifer discharge (Eltahir and Yeh, 1999). Thus, the exploration of long-term quantitative changes in the magnitude and distribution of hydrologic variables due to global changes in temperature and precipitation may be approached via a mechanistic analysis of the fundamental equations governing mass and energy balance in the unsaturated zones (Kay et al, 2005). Some illuminating preliminary studies have been done by performing water budget calculations in the light of various patterns describing precipitation and temperature changes (Panagoulia and Dimou, 1997). Using a conceptual rainfall-runoff model Chiew et al (1995) showed that the potential effects of changes in precipitation and temperature might translate in a significant increase in stream flow. As hydrologic research continues in this arena, knowledge of the impacts of these changes will add to the increasing evidence of the various effects of climate change on ecosystem response (see the review by Fuhrer, 2003).

Hydrologic Systems

It is common in engineering analysis to represent the different components of the hydrologic cycle as components of a complex system. In such a representation, each component acts as a subsystem with clearly defined boundaries. Inside the domain of a system component, certain variables of interest are defined, and their variability with respect to space and time are studied. These domain variables are subject to input functions from other subsystems, and transform the input variables into output variables that subsequently affect other subsystems. Clearly such conceptualization of the hydrologic cycle permits an understanding of the role of each component of the hydrologic cycle on the overall hydrologic response of an area. At the same time, it is possible to conceive the effect other hydrologic functions have on a particular component of interest. Furthermore the systems approach offers a means to quantitatively evaluate the magnitude and characteristics of variables in every system component. This approach has generated a large variety of hydrologic simulation models for multitude of practical applications.

Figure 1.2 shows a simplified systems representation of the hydrologic cycle described above. Each subsystem is represented as a rectangle. The arrows represent relationships between the different subsystems.

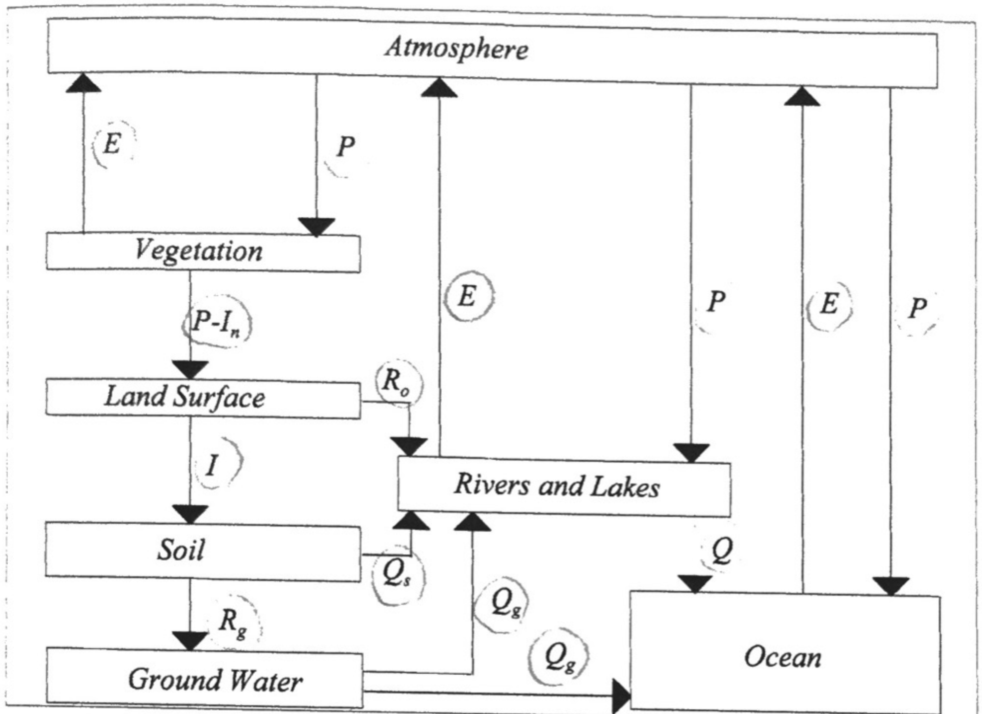

Figure 1.2: A Systems Representation of the Hydrologic Cycle

We remark again that this is a general, simplified, overview of the hydrologic cycle. Applications to particular watersheds require an in depth identification and analysis of the dominant processes, and a corresponding elimination of relatively unimportant ones. Other versions of Figure 1.2 may be applied in regions with different conditions. For example, there might be a snowpack subsystem that inputs snowmelt to the land surface subsystem; the soil subsystem may return some water back to the land surface (a process called exfiltration), where it is subject to evaporation; in the vicinity of a lake or a river, the soil subsystem may receive water from the river during times of high river stage, in which case the direction of the arrows may reverse; a similar phenomenon may occur between the groundwater and the river subsystem.

Therefore, a particular version of the hydrologic cycle system should be constructed to satisfy: (1) the project objectives, and (2) the specific hydrologic conditions of the watershed in question. The objectives to be accomplished determine the type of hydrologic model to use, the variables involved, and the required data to collect. The hydrologic conditions in a region determine the inner structure of the model and the inter-relation between the different system components. In a multi-disciplinary field as hydrology, the objectives of the hydrologic tasks must be clearly stated *a priori*. For example, the determination of the hydrologic regime in an area requires an entirely different model from that needed for the evaluation of the impact of agricultural tile drainage on streamflow.

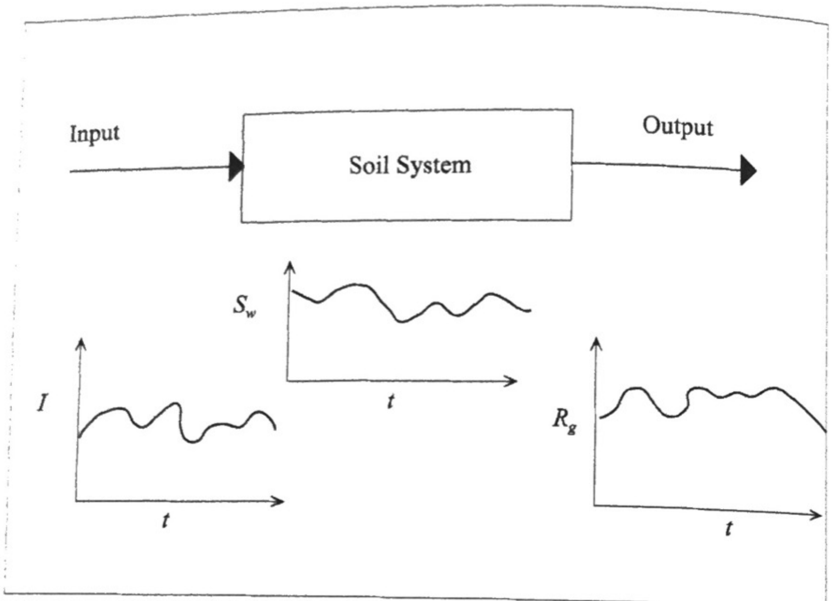

Figure 1.3: System Representation of Soil Moisture

Once the structure of a hydrologic model has been determined, the systems approach method calls for an individual analysis of each subsystem. Figure 1.3 shows an example of the soil subsystem in a watershed. Input variables to the soil system are the infiltration from the land surface, the subsurface flow from nearby rivers and lakes, and the possible capillary rise from the groundwater system. Output variables from the soil system might be composed of groundwater recharge, exfiltration to the land surface system, and subsurface flow to nearby rivers and lakes. The space and time evolution of each of these variables is analyzed and their combined effect on the system variable, in this case soil-water content, is quantified. The output variables are then quantified after determining specific functional relationships between the output variables, the system variable, and the input variables. These functional relationships are derived from the application of fundamental physical, chemical, and biological laws, and the application of mathematical methods. The process is repeated for all the system components. The result is a conceptual model of the hydrologic cycle designed to satisfy a specific set of project objectives. For an in depth treatment of the application of systems theory to hydrology see Singh (1988).

Physical Laws of Application in Hydrology

In the analysis of hydrologic systems, and especially in the determination of functional relationships between input, storage and output variables, several fundamental physical laws are applied. The most important physical laws with application in hydrologic analysis are as follow.

(1) The law of conservation of mass.
Mass is neither created nor destroyed. It is only transformed.

(2) Newton's laws of motion.
Law of conservation of momentum: *the momentum of a body remains constant unless the body is acted upon by a force.*

Force equals mass times acceleration: *the rate of change of momentum of a body is proportional to the net force acting on the body and is in the same direction as the net force.*

Law of action and reaction: *for every net force acting on a body, there is a corresponding force of the same magnitude exerted by the body in the opposite direction.*

(3) Laws of thermodynamics.
Law of conservation of energy: *energy is neither created nor destroyed. It is only transformed.*

Part of the energy transformed into work is lost to other forms of energy: *no process is possible in which the sole result is the absorption of heat and its complete conversion into work.*

(4) Fick's first law of diffusion.
Contaminant substances move from high to low concentration locations: *a diffusion substance moves from where its concentration is larger to where its concentration is smaller at a rate that is proportional to the spatial gradient of concentration.*

Application of these and other biological and chemical laws to different hydrologic processes and systems, in conjunction with the adoption of simplifying assumptions the use of mathematical methods, and the verification with via field experimentation constitutes the scientific method of hydrologic analysis.

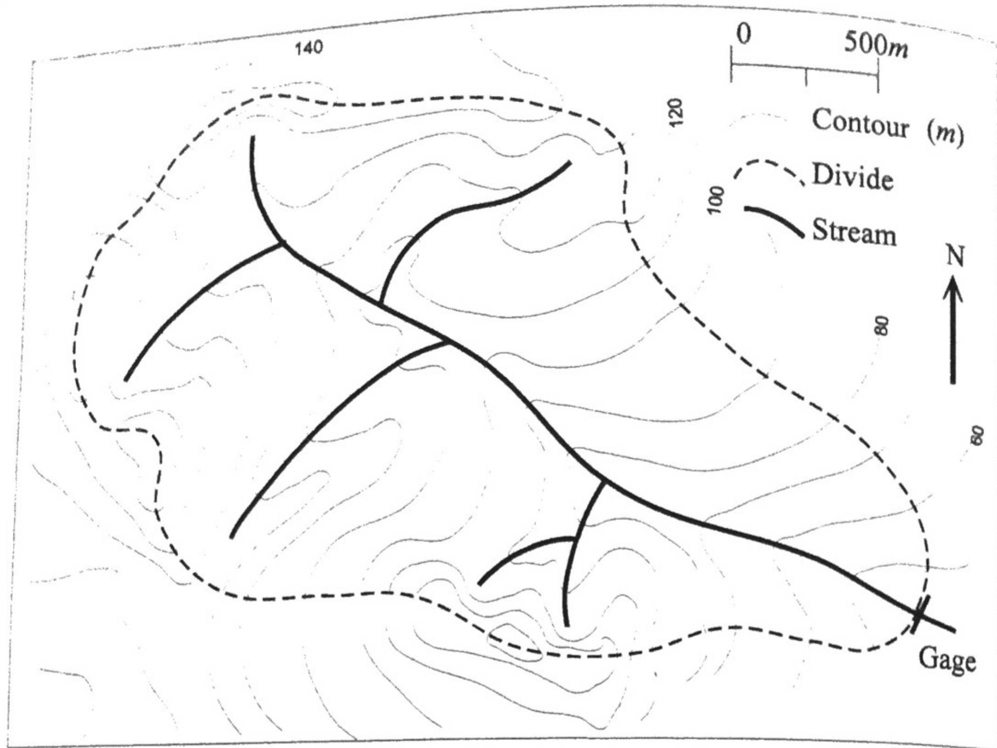

Figure 1.4: Delineation of a Watershed on a Topographic Map

The Concept of a Watershed

In thermodynamics, and in fluid mechanics, you learned that the fundamental laws of physics must be applied to an enclosed system. Similarly, hydrologists usually apply the mass conservation equation and other physical laws to an enclosed geographic region in order to establish its basic hydrologic characteristics. This geographic region is then subdivided into different hydrologic subsystems for specific analyses required by a set of project objectives, as described before. The fundamental geographic unit of hydrologic analysis is the watershed (also called the drainage basin, river basin, or catchment). The watershed is defined as the area that topographically appears to contribute with all the water that flows through a given cross section of a stream. Figure 1.4 shows the watershed contributing to a streamflow gage.

The surface trace of the boundary that delimits a watershed is called a divide, and it marks a boundary between flowing waters. Watershed boundaries do not cut through a stream, and surface waters will not flow through a correctly-drawn divide. In principle, most of the water precipitated within a watershed boundary, eventually passes through the gaging station. The horizontal projection of the area of a watershed is called the drainage area of the stream, or above the stream. The location of the gage is determined by the particular project objectives. Usually a water resource or environmental project is (or will be) near the gage. Once a gage has been located, the delineation of the corresponding watershed is important, since the characteristics of the watershed control many hydrologic processes. In principle, a large portion of the water passing through the stream cross section at the gage originated as precipitation on the drainage area.

To trace the divide of a watershed, a hydrologist needs a topographic map. Starting at the gage, a line is drawn away from the left or right bank, maintaining it always at a 90^0 angle with the contour lines. The hydrologist continues drawing the line until its trend is generally opposite to the direction in which it began and is generally above the headwaters of the stream network. The line is returned to the starting point on the other bank. The divide should pass along the highest points in the region. Mountain tops and mountain ranges should be traced longitudinally along their cliffs. The divide should never cross a stream. By visual inspection, the hydrologist should be able to visualize any drop of water precipitated inside the watershed to eventually appear at the outlet of the watershed (the gage). Delineation of urban watersheds requires storm sewer maps, in addition to topographic maps. In many situations the topographic divide does not coincide with the real divide, because city development may have altered the natural drainage of the watershed to satisfy other technical requirements. Delineation of watershed divides for groundwater studies require geological maps which can provide information of contributing areas from/to surrounding watersheds. Finally, watersheds may be subdivided into sub-watersheds where physical, environmental, or engineering aspects may require more detailed studies of hydrologic characteristics.

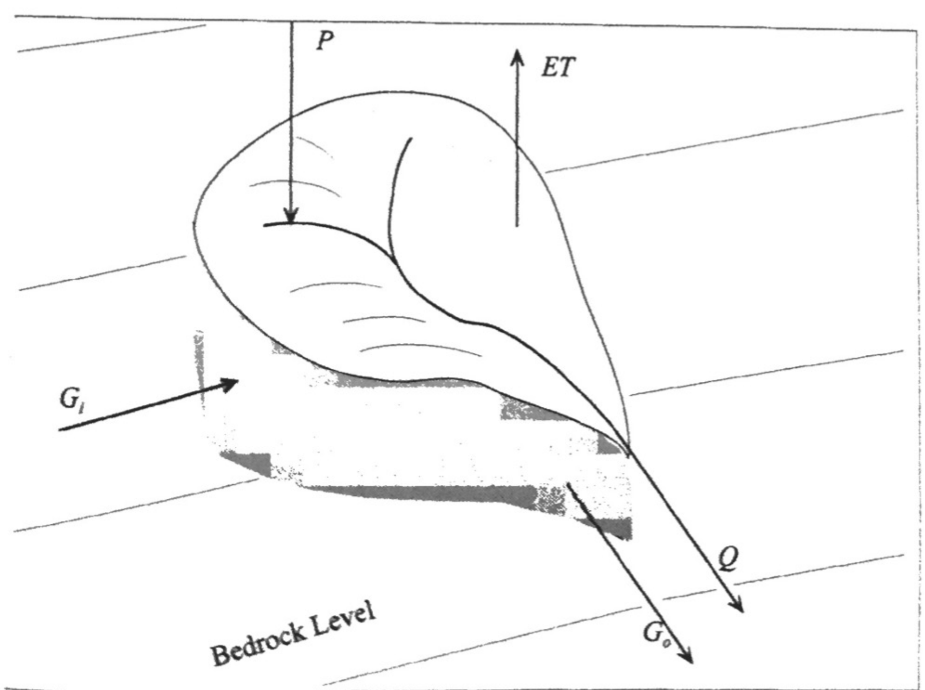

Figure 1.5: General Watershed Water Balance

It is important to remark that, having defined the system and its boundaries, by convention any quantity of water contributing to the system (i.e., any inflow of water) has a positive sign, and any quantity leaving the system (i.e., any outflow of water) has a negative sign. This is important since in certain cases the system boundary is set in such a way that a quantity may have a different sign than that described by equation (1.1). The way in which the system boundary is set depends on the objectives of the project. For example, if the objective is to establish a watershed surface water balance, then the ground surface, rather than the bedrock, should be the lower boundary. In this case the infiltration, I, which does not appear in equation (1.1), is a quantity that represents water leaving the surface, and thus has a negative sign. On the other hand, if the objective is to establish a water balance for the soil system, then the upper boundary should be the ground surface, and the bottom boundary should be the water table. In this case, the infiltration represents water entering the system, and thus has a positive sign. Therefore, consistency between project objectives, system setup, and algebraic signs of hydrologic quantities is important when using water balance calculations.

Another important aspect to remember is that equation (1.1), or any other similar expression involving hydrologic quantities, is a theoretical mass conservation application that assumes accuracy in every quantity. Measurement of hydrologic, climatic, and environmental variables is accomplished through inexact procedures in most practical situations. Even with use of sophisticated instrumentation, most measurement of hydrologic variables is subject to measurement errors varying from 2% to 20%, depending on the quantity, instrument type, and network density. These errors are reflected upon every calculation that uses field-based data. Therefore equation (1.1) is not fully satisfied when real data is substituted into the different variables. In practice, there is a discrepancy term in the right side that accounts for the combined errors in the different measured variables.

Equation (1.1) is the general water balance statement for a watershed. Depending on project objectives, an equivalent water balance equation may be written for a short or a long period of time; for a natural watershed or an artificially-created boundary; for water bodies such as lakes, reservoirs, or groundwater basins; for the region above the ground surface, that below surface, or the entire one. In each case, the system boundaries are different, some hydrologic functions may or may not appear, and the signs of each quantity vary.

Consider for example the water balance of the soil system. Figure 1.7

represents a typical unsaturated zone, or soil profile. The upper boundary is the ground surface, the lower boundary is the water table, and the lateral boundary is the watershed divide. Imagine that the objective of the project is to estimate the effect of a drastic reduction in the watershed infiltration due to a watershed-wide deforestation project. Neglecting the capillary fringe, and the exfiltration flow, and using previously-defined variables, the water balance equation for the soil system is

$$I - ET - Q_s - R_g = \Delta S_w \tag{1.2}$$

where

ΔS_w = change in soil-water storage

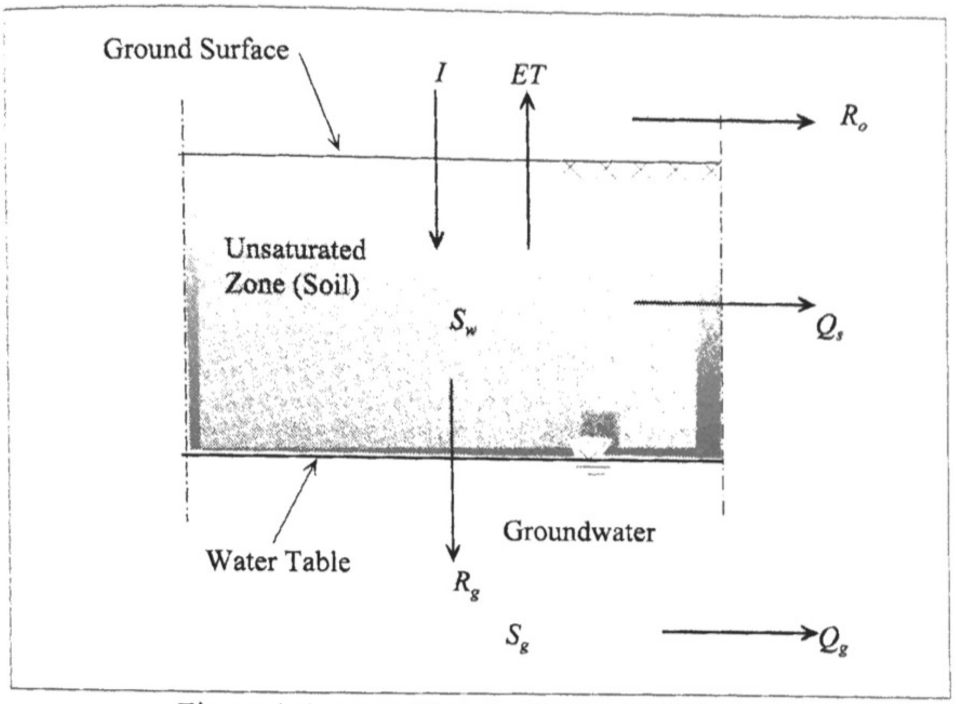

Figure 1.6: Water Balance for the Soil System

Again the units of each variable should be written in the form of depth uniformly spread over the entire watershed. Equation (1.2) could be written on an hourly, daily, monthly of annual basis to observe the time evolution of the different variables. If the balance equation is written for a year, the storage term may be negligible. For instance, if the balance equation is written for a year beginning at the end of the dry season, and ending at the end of the dry season of the following year, there is reason to believe that the net change in the soil-water storage is very small and thus $\Delta S_w \rightarrow 0$. This is a typical assumption in annual water balance calculations of surface and subsurface hydrologic systems. In water balance calculations covering shorter periods of time this assumption is not valid.