

# 1 INTRODUCTION

## 1.1 DEFINITION AND SCOPE

Hydrology is literally the science of water. Etymologically, the word has its roots in ancient Greek, and is a composite, made up of  $\acute{\upsilon}\delta\omega\rho$ , water, and  $\lambda\acute{o}\gamma\omicron\varsigma$ , word. Obviously, defined this way, the term is much too broad to be very useful, as it would have ramifications in all scientific disciplines.

Actually, the word hydrology has not always been well defined and even as recently as the 1960s it was not very clear exactly what hydrology was supposed to cover and encompass. Price and Heindl (1968), in a survey of many of the definitions that had appeared in the literature over the previous 100 years, were compelled to conclude that the question “What is Hydrology?” had not been resolved by their review. Still, they felt that, in general, there seemed to be a consensus that hydrology is a physical science, which is concerned mainly with the water cycle of land and near-shore areas; moreover, there had been a tendency to broaden the term rather than to narrow it, even to the point of including socio-economic aspects.

Over the past few decades, however, with the growing activity level and the increasing maturity of this field of endeavor, a more precise definition has emerged. Hydrology is now widely (see, for example, Eagleson, 1991) accepted to be the science that deals with those aspects of the cycling of water in the natural environment that relate specifically with

- *the continental water processes*, namely the physical and chemical processes along the various pathways of continental water (solid, liquid and vapor) at all scales, including those biological processes that influence this water cycle directly; and with
- *the global water balance*, namely the spatial and temporal features of the water transfers (solid, liquid and vapor) between all compartments of the global system, i.e. atmosphere, oceans and continents, in addition to stored water quantities and residence times in these compartments.

Because it is defined as being concerned specifically with continental water processes, hydrology is a discipline distinct from meteorology, climatology, oceanology, glaciology and others that also deal with the water cycle in their own specific domains, namely the atmosphere, the oceans, the ice masses, etc., of the Earth; at the same time, however, hydrology integrates and links these other geosciences, in that through the global water balance it is also concerned with the exchanges of water between all these separate compartments.

With this definition it is now also possible to delineate the practical scope of hydrologic analysis in engineering and in other applied disciplines. It consists of the determination of the amount and/or flow rate of water that will be found at a given location and at a given time under natural conditions, without direct human control or intervention. The latter specification, that no human control be involved, is necessary to distinguish hydrology from the related discipline of hydraulics. Hydraulics is concerned with the study of controlled fluid motion in well-defined and often in human-made environments. For instance, problems involving pipe flow, irrigation water distribution or pumping of groundwater are not hydrologic in nature, but are more properly assigned to the realm of hydraulics.

1.2 THE HYDROLOGIC CYCLE

The water cycle, also called the hydrologic cycle, refers to the pathway of water in nature, as it moves in its different phases through the atmosphere, down over and through the land, to the ocean and back up to the atmosphere. When atmospheric water vapor condenses and precipitates over land, initially it moistens the surface and some amount of it is stored as *interception*, which later evaporates. As *precipitation* (and in a similar way *snowmelt*) continues, part of it may flow over the surface in the form of *overland flow* or *surface runoff*, and part of it may enter into the soil as *infiltration*. This surface runoff soon tends to collect locally, either in puddles or small ponds as *depression storage*, or in gullies or larger channels where it continues as *streamflow*, which ultimately ends up in a larger water body, such as a lake or the ocean. Streamflow is normally described by a *hydrograph*, that is the rate of flow at a gaging station as a function of time. The infiltrated water may flow rapidly through the near-surface soil layers to exit into springs or adjacent streams, or it may percolate more slowly through the profile to join the *groundwater*, which sooner or later seeps out into the natural river system, lakes and other open water bodies; part of the infiltrated water is retained in the soil profile by capillarity and other factors, where it is available for uptake by the roots of vegetation.

Soil layers and other geologic formations, whose pores and interstices can transmit water, are called *aquifers*. When an aquifer is in direct contact with the land surface, it is referred to as *unconfined*. The locus of points in an unconfined aquifer, where the water pressure is atmospheric, is called the *water table*. Although the water table is not a true free surface separating a saturated zone from a dry zone, it is sometimes assumed to be the upper boundary of the groundwater in an unconfined aquifer. The partly saturated zone in an unconfined aquifer, between the water table and the ground surface, is sometimes referred to as the *vadose zone*. In an unconfined aquifer, the term *groundwater* refers usually to the water found below the water table; *soil water* or *soil moisture* refers to the water above the water table. A water bearing geologic formation, that is separated from the surface by an impermeable layer, is referred to as a *confined aquifer*. Streamflow is fed both by surface runoff and by subsurface flow from riparian (i.e. located along the banks) aquifers. The streamflow, resulting from groundwater outflow is often called *base*

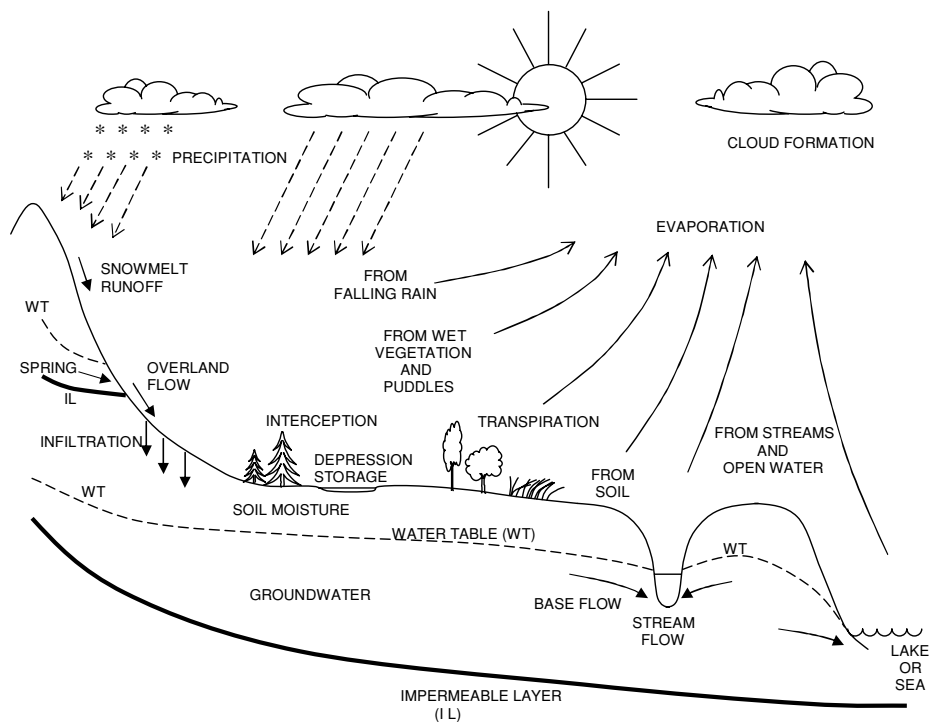


Fig. 1.1 Sketch of some of the main processes in the land phase of the water cycle.

flow; in the absence of *storm flow* or *storm runoff* caused by precipitation, base flow is also referred to as *drought flow* or *fair weather flow*.

Finally, the hydrologic cycle is closed by *evaporation*, which returns the water, while in transit in the different flow paths and stages of storage along the way, back into the atmosphere. When evaporation takes place through the stomates of vegetation, it can be referred to as *transpiration*. Direct evaporation from open water or soil surfaces and transpiration of biological water from plants are not easy to separate; therefore the combined process is sometimes called *evapotranspiration*. Evaporation of ice is commonly referred to as *sublimation*. While these distinctions are useful at times, the term *evaporation* is usually adequate to describe all processes of vaporization. Some of the main processes are drawn schematically in Figure 1.1.

1.3 SOME ESTIMATES OF THE GLOBAL WATER BALANCE

Numerous studies have been carried out to estimate the magnitude of the most important components of the water budget equations on a global scale. Because the available data base required for this purpose is still far from adequate, several of the methods used in these estimates may be open to criticism. Nevertheless, there is a fair agreement among

Table 1.1 Estimates of world water balance (m y<sup>-1</sup>)

Reference	Land (1.49 × 10 <sup>8</sup> km <sup>2</sup> )			Oceans (3.61 × 10 <sup>8</sup> km <sup>2</sup> )		Global <i>P</i> = <i>E</i>
	<i>P</i>	<i>R</i>	<i>E</i>	<i>P</i>	<i>E</i>	
Budyko (1970, 1974)	0.73	0.31	0.42	1.14	1.26	1.02
Lvovitch (1970)	0.73	0.26	0.47	1.14	1.24	1.02
Lvovitch (1973)	0.83	0.29	0.54	—	—	—
Baumgartner and Reichel (1975)	0.75	0.27	0.48	1.07	1.18	0.97
Korzun <i>et al.</i> (1978)	0.80	0.315	0.485	1.27	1.40	1.13

some of the calculated values and, within certain limits, they provide a useful idea of the long-term average balance in different climatic regions of the world.

As shown in Table 1.1, the average annual precipitation and also evaporation are of the order of 1 m for the entire Earth. Over the landsurfaces the average precipitation intensity, *P*, is about 0.80 m y<sup>-1</sup>, whereas the corresponding average evaporation, *E*, is around 0.50 m y<sup>-1</sup> or about 60% to 65% of the precipitation. Under steady conditions, that is for long time periods, the remainder can be considered to be runoff from the landsurfaces into the oceans, *R* (expressed as height of water column per unit of time), or

$$R = P - E$$

(1.1)

Averaged over all continents and over long time periods, the annual runoff *R* is therefore around 35% to 40% of the precipitation. Except for South America and Antarctica (see Table 1.2), the values for the individual continents are not very different from the global values. Precipitation and streamflow runoff measurements have been and are being made routinely in many places on Earth. In contrast, evaporation has not received as much attention and no systematic measurements are available.

Estimates of the average distribution of water in different forms expressed as depth of water covering the globe, assumed to be a perfect sphere, are given in Table 1.3. These indicate that the 1 m of average annual precipitation is relatively large as compared to the active fresh water on Earth, that is the water which is not stored in permanent ice and deep groundwater. This means that the turnover of the active part of the hydrologic cycle is rather fast, and that the residence times in some of the major compartments of the water cycle are relatively short; the mean residence time can be taken as the ratio of the storage and the flux in or out of storage. For example, a continental runoff rate of 0.30 m y<sup>-1</sup> (Table 1.1) and a storage in the rivers of (0.003/0.29) m of water on the 29% of the world occupied by land, gives a mean residence time of the order of 13 days for the rivers of the world. Similarly, a global evaporation rate of 1 m y<sup>-1</sup>, with 0.025 m of storage in the atmosphere, leads to a mean residence time of the order of 9 days for the

Table 1.2 Some estimates of the mean precipitation (and river runoff) from available data for the continents (in m y<sup>-1</sup>) (\*)

	Europe	Asia	Africa	North America	South America	Australia and Oceania	Antarctica
Percent of land area	6.7	29.6	20.0	16.2	12.0	6.0	9.5
Reference							
Lvovitch (1973)	0.734 (0.319)	0.726 (0.293)	0.686 (0.139)	0.670 (0.287)	1.648 (0.583)	0.736 (0.226)	— —
Baumgartner and Reichel (1975)	0.657 (0.282)	0.696 (0.276)	0.696 (0.114)	0.645 (0.242)	1.564 (0.618)	0.803 (0.269)	0.169 (0.141)
Korzoun <i>et al.</i> (1977)	0.790 (0.283)	0.740 (0.324)	0.740 (0.153)	0.756 (0.339)	1.600 (0.685)	0.791 (0.280)	0.165 (0.165)

\*The corresponding evaporation values can be determined with Equation (1.1).

Table 1.3 Estimates of different forms of global water storage (as depth in m over entire earth surface)

Source of data	Lvovitch (1970)	Baumgartner and Reichel (1975)	Korzun <i>et al.</i> (1978)
Oceans	2686	2643	2624
Ice caps and glaciers	47.1	54.7	47.2
Total ground water	117.6	15.73 (excluding Antarctica)	45.9
(Active ground water)	(7.84)	(6.98)	—
Soil water	0.161	0.120	0.0323
Lakes	0.451	0.248	0.346
Rivers	0.002 35	0.002 12	0.004 16
Atmosphere	0.0274	0.0255	0.0253

atmosphere. These are very short residence times. Moreover, as the oceans occupy about 71% of the Earth surface, the active fresh water in the hydrologic cycle is continually being distilled anew through ocean evaporation.

Maps depicting the approximate distribution of components of the water balance in different parts of the world have been presented by Lvovitch (1973), Budyko (1974), Baumgartner and Reichel (1975), Korzoun *et al.* (1977), and Choudhury *et al.* (1998). The relative and absolute magnitudes of the main components of the hydrologic cycle, namely *P*, *R* and *E*, can vary over a wide range from one location to another. Obviously, the long-term mean values of all three are negligible in desert locations. At the other extreme, maximal annual precipitation values of up to 26.5 m have been recorded in a mountainous monsoon environment (Cherrapunji, Meghalaya). Maximal mean evaporation values of

Table 1.4 Estimates of mean global heat budget at the earth surface in W m<sup>-2</sup>

Reference	Land			Oceans			Global		
	<i>R<sub>n</sub></i>	<i>L<sub>e</sub>E</i>	<i>H</i>	<i>R<sub>n</sub></i>	<i>L<sub>e</sub>E</i>	<i>H</i>	<i>R<sub>n</sub></i>	<i>L<sub>e</sub>E</i>	<i>H</i>
Budyko (1974)	65	33	32	109		11		80	16
					98		96		
Baumgartner and Reichel (1975)	66	37	29	108		16		76	20
					92		96		
Korzun <i>et al.</i> (1978)	65	36	29	121	109	12	105	89	16
Ohmura (2005)	62	36	26	125	110	15	104	85	19

up to 3.73 m y<sup>-1</sup> have been inferred for the Gulf Stream in the western Atlantic (Bunker and Worthington, 1976) and up to 4 or even 5 m y<sup>-1</sup> for the Gulf of Aqaba (Assaf and Kessler, 1976). Much research has been directed in recent years to study the evolution of today’s climate in response to increasing greenhouse gases in the atmosphere. Although the issue is far from resolved, there are some indications of an accelerating hydrologic cycle in several regions (see, for example, Brutsaert and Parlange, 1998; Karl and Knight, 1998; Lins and Slack, 1999).

The strong linkage between the water cycle and climate is further illustrated by the estimates of the mean global surface energy budget in Table 1.4. Over large areas and over sufficiently long periods, when effects of unsteadiness, melt and thaw, photosynthesis and burning, and lateral advection can be neglected, this surface energy balance can be written as

$$R_n = L_e E + H$$

(1.2)

where *R<sub>n</sub>* is the specific flux of net incoming radiation, *L<sub>e</sub>* is the latent heat of vaporization, *E* is the rate of evaporation, and *H* is the specific flux of sensible heat into the atmosphere. The major portion of the incoming radiation is absorbed near the surface of the Earth, and it is transformed into internal energy. The subsequent partition of this internal energy into long-wave back radiation, upward thermal conduction and convection of sensible heat *H*, and latent heat *L<sub>e</sub>E*, is one of the main processes driving the atmosphere. Table 1.4 indicates that the net energy is mainly disposed of as evaporation. Over the oceans, the latent heat flux *L<sub>e</sub>E* is on average larger than 90 percent of the net radiation. But even over the land surfaces of the Earth, *L<sub>e</sub>E* is on average still larger than half of *R<sub>n</sub>*.

Because the global patterns of heating force the circulation of the planetary atmosphere, the implications of this large latent heat flux are clear. As a result of the relatively large latent heat of vaporization *L<sub>e</sub>*, evaporation of water involves the transfer and redistribution of large amounts of energy under nearly isothermal conditions. Because, even at saturation, air can contain only relatively small amounts of water vapor, which can easily be condensed at higher levels, the air can readily be dried out; this release of energy through condensation and subsequent precipitation is the largest single heat source for the

atmosphere. Thus processes in the water cycle play a central role in governing weather and climate.

1.4 METHODOLOGIES AND PROCEDURES

This book aims primarily to describe the occurrence and the transport of water in its continuous circulation over the landsurfaces of the Earth. Before starting this task, it is worthwhile to review briefly the different strategies that are available and that can be used for this purpose.

1.4.1 *Statistical analysis and data transformation*

As observed in Section 1.2, one of the main practical objectives of hydrologic analysis is the determination of the quantity of water, in storage or in transit, to be found at a given time and place, free of any direct human control. When a reliable record of observed hydrologic data is available, a great deal can be learned simply by a statistical analysis of this record. Although such an approach is proper for stationary systems in the prediction of long-term behavior for general planning purposes, it cannot be used for short-term and emergency forecasting, for example, during floods, or for day-to-day resource management decisions. Furthermore, reliable records are available for only a few locations over a limited period of time, and practically never where needed. Therefore in hydrology the problem is often such, that a method must be devised to transform some available data, which are of no direct interest, to the required hydrologic information. For instance, the problem may consist of determining the rate of flow in a river at a given location either from a known flow rate at some other point upstream or downstream, or from a known rainfall distribution over the upstream river basin. In other cases, the problem may consist of deducing the basin evapotranspiration from soil and vegetation on the basis of available meteorological data.

1.4.2 *The “physical” versus the “systems” approach*

The hydrologic literature is replete with attempts at classifying the methodologies and paradigms that have been used to transform hydrologic input into hydrologic output information. Until a few years ago it had become customary to consider two contrasting approaches, namely the “physical” approach and the “systems” approach. In the physical approach the input–output relationship is sought by the solution of the known conservation equations of fluid mechanics and thermodynamics with appropriate boundary conditions to describe the flow and transport of water throughout the hydrologic cycle. This approach has obvious limitations; the physiographic and geomorphic characteristics of most hydrologic systems are so complicated and variable, and the degree of uncertainty in the boundary conditions so large, that solutions are feasible only for certain highly simplified situations. In other words, the properties of natural catchments can never be measured accurately enough, and solutions, based on internal descriptions starting from



first principles of fluid mechanics, can be obtained only for grossly idealized conditions, which are coarse approximations of any real situation.

The hydrologic “systems” (also “operational” or “empirical”) approach is presumably based on a diametrically opposite philosophy. In this approach the physical structure of the various components of the hydrologic cycle and their inner mechanisms are not considered; instead, each component, however it may be defined, is thought of as a “black box,” and the analysis focuses on discovering a mathematical relationship between the external input (e.g. rainfall, air temperature, etc.) and the output (e.g. river flow, soil moisture, evaporation, etc.). The structure of this mathematical relationship is mostly quite remote from the physical structure of the prototype phenomena in nature. This lack of correspondence between the inner physical mechanisms and the postulated functional formalisms makes this approach quite general operationally, because it permits the use of well-known algorithms and objective criteria in identification and prediction. However, this also underlies the main limitations of this approach. First, in assigning cause and effect the definition of input and output variables is mostly based on intuition guided by past experience, and the danger exists that some important phenomena are overlooked. Second, the best that can ever be expected with a black box approach is a satisfactory reproduction of a previously obtained input–output record; even when such data are available, it is difficult to accommodate fully the nonstationary effects in the system, and it is impossible to anticipate subsequent hydrologic changes, such as those resulting from urbanization, deforestation, reclamation, or climate change.

Because many hydrologic methods do not really fit in this physical-versus-empirical classification, a third possible approach was taken to be an intermediate one. In this view the performance of a hydrologic unit, say a catchment, is represented in terms of some idealized components or “grey boxes,” which correspond to recognizable elements in the prototype, whose input–output response functions are structured after solutions of some tractable or suitably simplified situations of the physical processes perceived to be relevant. This third way was often called the “conceptual model” approach.

At first sight, a classification based on three distinct approaches, namely physical, empirical and conceptual, may appear reasonable. However, it is less than obvious how this classification can be applied to specific cases. Indeed, one might ask what the difference is between physical and empirical. After all, the essence of physical science is experimentation and conceptualization. Moreover, the physical approach of one discipline is usually the empiricism or the conceptual model of another. For example, Newton’s “law” of viscous shear constitutes the physical basis of a wide area of fluid mechanics, whereas it represents a mere black box simplification in molecular physics. Darcy’s law is the physical basis of much of groundwater hydrology, but in fluid mechanics it can be considered an operational approach, to avoid the complexity of flow analysis in an irregular and ill-defined pore network. The same dilemma is inherent in most other special concepts used in hydrology. This ambiguous difference between physical, empirical and conceptual shows that the classification of the methodologies should be based on other criteria.



1.4.3 *Spatial scale and parameterization*

*General approach*

All natural flow phenomena are governed by the principles of conservation of mass, momentum and energy, which can be expressed by a number of equations to provide a mathematical description of what goes on. However, because there are normally more dependent variables than available conservation equations, in order to close the system, additional relationships must be introduced. These closure relationships, also called *parameterizations*, relate some of the variables with each other to describe certain specific physical mechanisms; the mathematical form of these relationships, and the values of the material constants or *parameters* are usually based on experimentation.

A second point is that any physical phenomenon must be considered at a given scale; this scale is the available (depending on the data) or chosen (depending on the objectives of the study) resolution. It will become clear later on in this book that, while the fundamental conservation equations remain unaffected by the scale at which the phenomenon is being considered, most closure relationships in them are quite sensitive to scale. Indeed, a parameterization can be considered as a mathematical means of describing the subresolution (or microscale) processes of the phenomenon, in terms of resolvable scale (or macroscale) variables; these macroscale variables are the ones, which can be treated explicitly in the analysis or for which measured records are obtainable. Thus, the details of the microscale mechanisms are not considered explicitly, but their statistical effect is formulated mathematically by a parameterization in terms of macroscale variables.

All this suggests that a sound criterion to distinguish, in principle at least, one approach from another, may be the spatial scale at which the internal mechanisms are parameterized. For example, Newton's equation for viscous shear stress (see Equation (1.12) below) is a parameterization in terms of variables typically at the millimeter to centimeter scale; however, it reflects momentum exchanges at molecular scales, which are orders of magnitude smaller. The hydraulic conductivity is a parameter at the so-called Darcy scale (see Chapter 8), namely a scale somewhere intermediate between the Newtonian viscosity (or Navier–Stokes) scale for water and air inside the soil pores, on the one hand, and the field scales for infiltration and drainage, on the other. Several spatial scales are illustrated with the corresponding characteristic temporal scales in Figure 1.2 for some general types of water transport processes as they have been considered in hydrologic studies.

On the land surfaces of the Earth, the catchment or river basin sizes appear as scales of central importance. The terms *basin*, *catchment*, *watershed* and *drainage area* are roughly synonymous and are often used interchangeably. A basin can be defined as all of the upstream area, which contributes to the open channel flow at a given point along a river. The size of the basin depends on the selection of the point in the river system under consideration. Usually this point is taken, where the river flows into a large water body, such as a lake or the ocean, or where it changes its name as a tributary into a larger river. However, a basin or catchment can also be defined by any point along the river, where the river flow is being measured. Basins are delineated naturally by the land surface topography, and topographic ridges are usually

taken as their boundaries; they can be considered as the natural conveyance systems for mass and energy on the land surfaces of the Earth. In meteorology, the concern is more on atmospheric motions and weather systems, and this has led to a somewhat different scale classification; an example of a commonly used classification is shown in Table 1.5.

Table 1.5 A common scale classification in the atmosphere (after Orlanski, 1975)

Nomenclature	Scale range
Micro $\gamma$	<20 m
Micro $\beta$	20–200 m
Micro $\alpha$	200 m–2 km
Meso $\gamma$	2 km–20 km
Meso $\beta$	20 km–200 km
Meso $\alpha$	200 km–2000 km
Macro $\gamma$	>2000 km

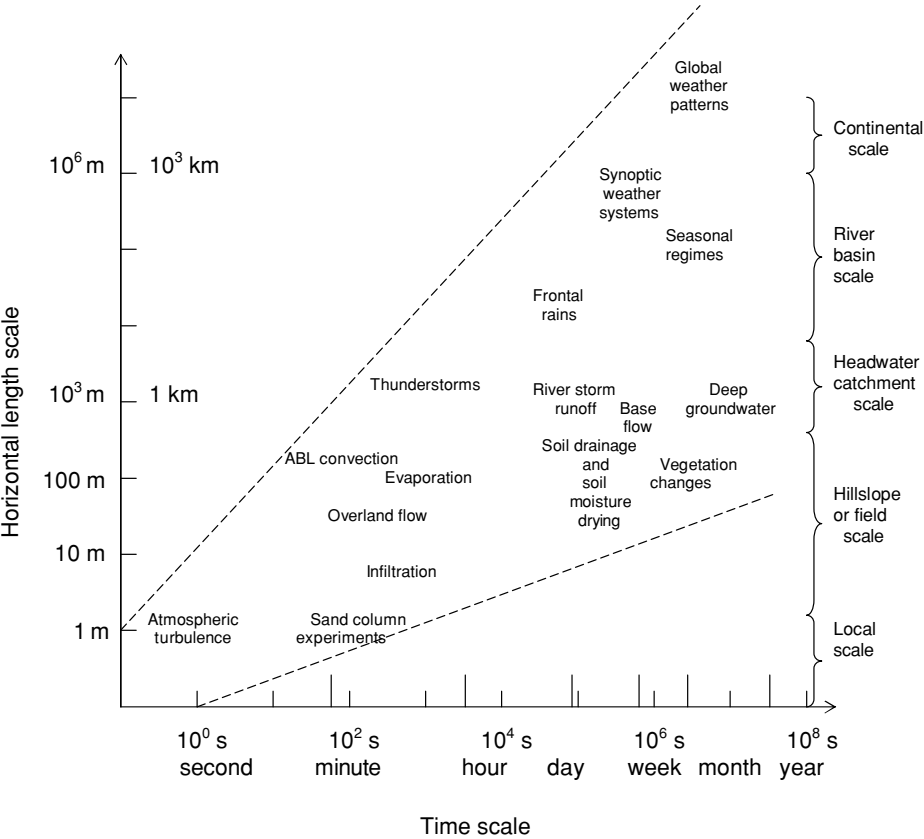


Fig. 1.2 Approximate ranges of spatial and temporal scales of some common physical processes that are relevant in hydrology.