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Introduction

Soil moisture and plants are the two main subjects of this book, the former being at the center of the hydrologic cycle and the latter ones representing the primary component of terrestrial ecosystems. The analysis of their interrelationships points at the very heart of ecohydrology, the science that studies the mutual interaction between the hydrologic cycle and the ecosystems (Rodríguez-Iturbe, 2000; Porporato and Rodríguez-Iturbe, 2002).

The interaction between water balance and plants is responsible for some of the fundamental differences among various biomes (e.g., forests, grasslands, savannas) and for the developments of their space–time patterns. The first objective of ecohydrology is thus to understand the intertwined characteristics of climate, soil, and vegetation that make a biome what it is, and to relate hydrologic dynamics to the space–time response of vegetation in a region. Throughout the book, we will concentrate on water-controlled (or water-stressed) ecosystems, where water may be a limiting factor not only because of its scarcity but also because of its intermittent and unpredictable appearance.

Understanding what is the relative importance of the interactions between soil moisture and plants and how this importance changes from one ecosystem to another will be the guide to our modeling effort, which in many ways is inspired by the principle that "the purpose of models is not to fit the data but to sharpen the questions" (Karlin, 1983). We will use simplified analytical models to describe the various mechanisms responsible for the dynamics of soil moisture, from the most basic ones at a point to the more complicated cases involving different spatial and temporal scales. The necessary assumptions will be stated clearly to warn the reader about the possible limitations of each analysis, always striving for analytical tractability and results of some general validity.

In this introductory chapter we give an overview of the problems that will be analyzed in the following. The discussion of different examples to explain the philosophy underlying the developments of the analysis mostly follows the general papers by Rodríguez-Iturbe et al. (2001a) and Porporato and Rodríguez-Iturbe (2002).

1.1 Ecohydrology of water-controlled ecosystems

Water-controlled ecosystems are complex, evolving structures whose characteristics and dynamic properties depend on many interrelated links between climate, soil, and vegetation (Figure 1.1). On one hand, climate and soil control vegetation dynamics (e.g., Lange et al., 1976; Boyer, 1982; Jones, 1992; Kramer and Boyer, 1995; Larcher, 1995), on the other hand vegetation exerts important control on the entire water balance and is responsible for many feedbacks to the atmosphere (e.g., Schlesinger et al., 1990; Kutzbach et al., 1996; Zeng et al., 1999). Many important issues depend on the quantitative understanding of the ecohydrology of water-controlled ecosystems, including environmental preservation and proper management of resources (e.g., Noy-Meir, 1973; Shmida et al., 1985; Archer et al., 1988; Scholes and Walker, 1993; Archer, 1994).

Soil moisture is the key variable synthesizing the action of climate, soil, and vegetation on the water balance and the dynamic impact of the latter on plants (e.g., Noy-Meir, 1973; Lange et al., 1976; MacMahon and Schimpf, 1981; Tinley, 1982; Stephenson, 1990; Neilson, 1995; Laio et al., 2001a; Porporato et al., 2001; Rodríguez-Iturbe et al., 2001a; Porporato and Rodríguez-Iturbe, 2002). If rainfall, at a first analysis, may be regarded as a gross surrogate of soil moisture to determine plant ecosystem structure at the continental scale (e.g., Figure 1.2), the actual assessment of plant conditions depends on soil moisture dynamics *in situ*. This is clear in Figure 1.3, which shows the importance of the variability of soil moisture, as affected by both soil texture and interannual rainfall fluctuations, in the recruitment of *Bouteloua gracilis* (blue grama), a small dominant grass in the Colorado steppe (Laurenroth et al., 1994).

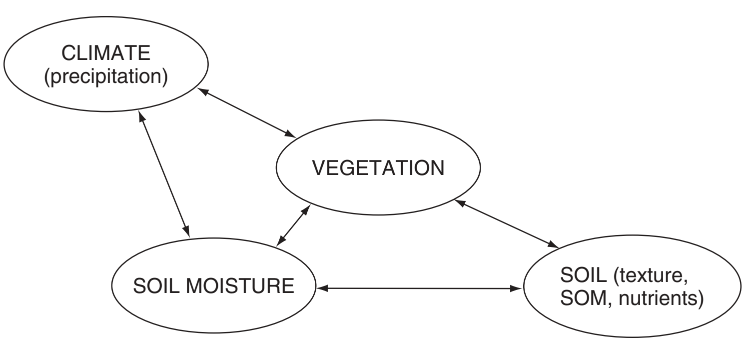

Figure 1.1 Schematic representation of the climate, soil, and vegetation system (SOM = Soil Organic Matter).

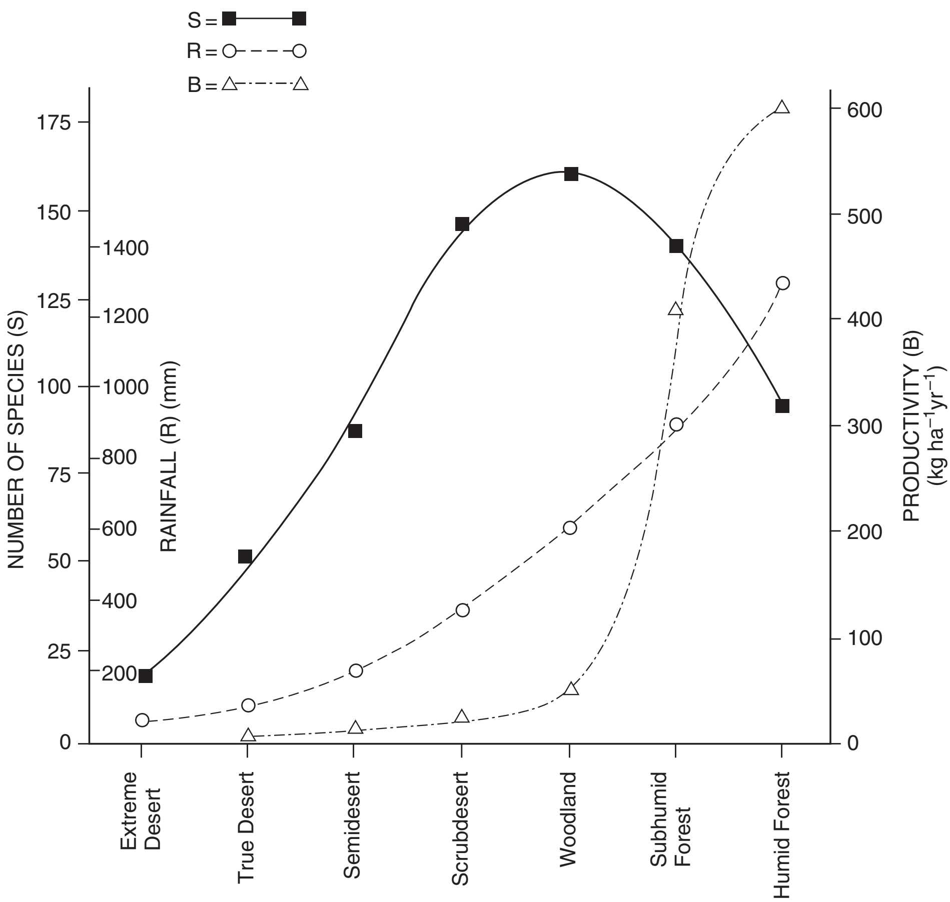

Figure 1.2 General link between precipitation, biomass, and biodiversity in water-controlled ecosystems. After Shmida and Burgess (1988).

The idea that soil moisture dynamics is at the core of water-controlled ecosystems is not new. It permeated some of the pioneering and seminal works in the field, such as those by Gardner (1960), Cowan (1965), Noy-Meir (1973), and Eagleson (1978a, 1978b, 1982) among others. As stated by Noy-Meir (1973), the soil is the store and regulator in the water flow system of the ecosystems, both as a temporary store for the precipitation input allowing its use by organisms and as a regulator controlling the partition of this input between the major outflows: runoff, evapotranspiration redistribution, and the flow between the different organisms.

Plants play a special role in water-controlled ecosystems, having an active role in water use that heavily conditions the soil water balance and at the same time being impacted by the arid conditions they contribute to produce.

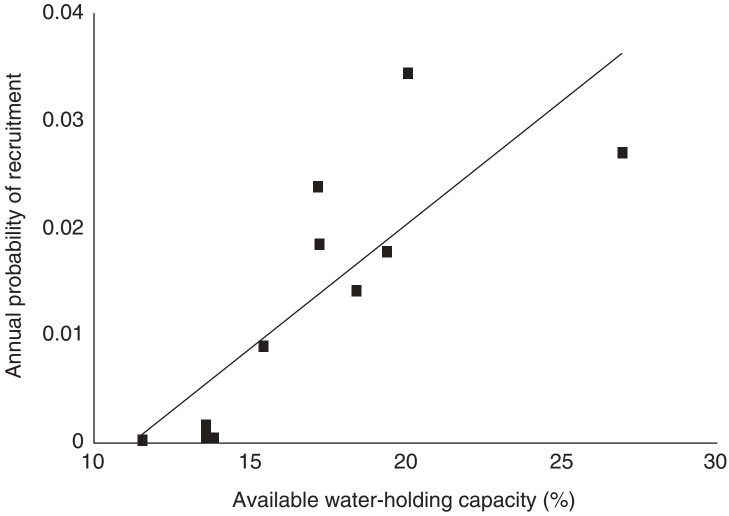

Figure 1.3 Soil-moisture dependence of recruitment of new plants of *Bouteloua gracilis* for a site in Colorado. After Laurenroth et al. (1994); see also Section 5.3.

Differences in soil moisture dynamics are among the principal reasons for the existence of particular functional vegetation types and ecosystem structures. Special adaptation to water stress and intra/inter-species interactions are likely connected to the dynamics of the climate–soil–vegetation system and both the coexistence of different functional vegetation types and the development of temporal and spatial vegetation patterns depend on the emergence of specific temporal niches of soil water and nutrient availability (Cody, 1986; Scholes and Archer, 1997). Chapters 2, 3, 4, and 6 will set the stage to model the basic interaction between soil moisture and plants.

1.2 Simplifying assumptions

There are two characteristics that make the quantitative analysis of the problem especially daunting (Rodríguez-Iturbe et al., 2001a): (i) the very large number of different processes and phenomena that make up the dynamics, and (ii) the extremely large degree of variability in time and space that the phenomena present. The first of the above characteristics obviously calls for simplifying assumptions in the modeling scheme while still preserving the most important features of the dynamics, while the second one calls for a stochastic description of some of the processes controlling the overall dynamics.

In the attempt to capture the essential dynamics of ecosystems, plants responding in a similar way to a syndrome of environmental factors are often grouped together referring to plant functional types (Gitay and Noble, 1997). This is extremely useful for providing results that are applicable to different ecosystems throughout the world, so that the analysis may be generally referred to typical average conditions rather than to particular places or species. It does not mean, however, that the specific adaptation mechanisms to water stress and intra/inter-species interactions (e.g., competition for water and reproduction) are not essential for the dynamics of a particular biome. As shown in Figure 1.4, the impact of soil moisture on water stress may be quite different among species (as well as each individual) and this may in turn drive the emergence of specific temporal niches of soil water and nutrient availability and patterns of coexistence (e.g., Fernandez-Illescas et al., 2001; Porporato et al., 2001). As noted by Tilman (1996), biodiversity seems to stabilize ecosystem properties: while interspecific competition magnifies the effect of a perturbation on the abundances of individual species, the competitive release experienced by disturbance-resistant species acts to stabilize total biomass in species-rich communities.

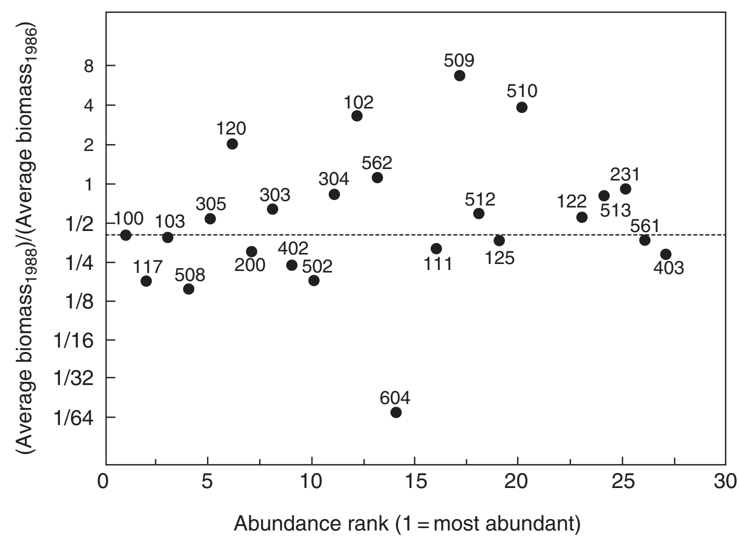

Figure 1.4 Change in the average biomass of 24 abundant species, from before the drought (1986) to the peak of the drought (1988) in a long-term study of 207 grassland plots in Minnesota, graphed against their ranked abundance. The dashed line shows the response of community biomass with each dot representing a species identified by the number. Notice the quite diversified response to drought and how many species performed better during drought than did plant community biomass. After Tilman (1996).

1.3 Levels of description

As it is typical of complex systems, the dynamics of the climate–soil–vegetation system presents different levels of complexity according to the scale of interest (Porporato and Rodríguez-Iturbe, 2002): the importance of the various hydrologic processes may be different whether one considers daily, seasonal, or interannual fluctuations or point (i.e., plot), regional (i.e., hill-slope to catchment), or continental scales. Such a distinction of scales is important as it naturally suggests different levels of analysis in which only the main interactions may be retained (Figure 1.5).

A first basic level of analysis of the climate–soil–vegetation system is at the spatial scale of a few meters (e.g., plot scale) and at the temporal scale of the growing season. At such scales, soil moisture dynamics directly impacts vegetation through plant water stress, while the rainfall input and the soil characteristics may be considered as external components (Figure 1.6). The first part of the book deals with this level (Chapters 2–6).

A second and more complex level of analysis involves the links between soil moisture, soil nutrient cycles, and the related evolution of soil properties. Such factors are all interrelated with vegetation dynamics and represent an area relatively less studied by both ecologists and hydrologists. In Chapter 10 we

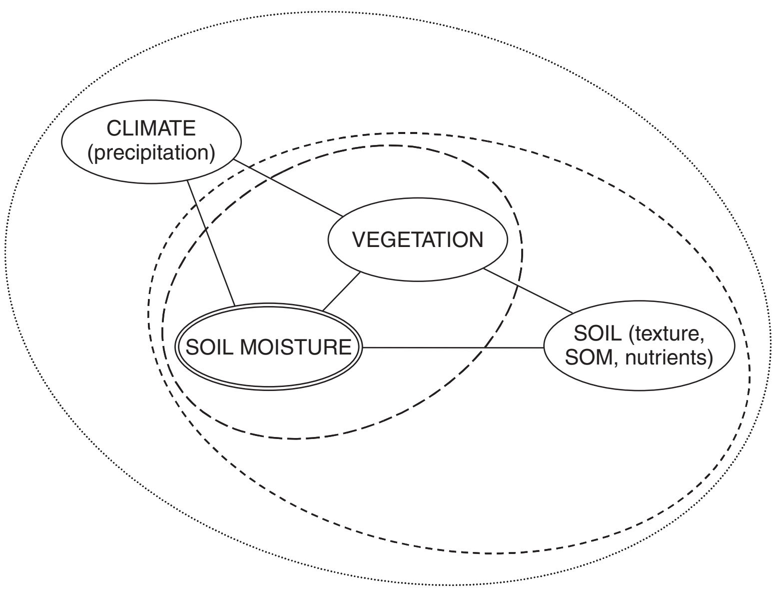

Figure 1.5 Levels of description of the climate–soil–vegetation system having at the center soil moisture (SOM = Soil Organic Matter). After Porporato and Rodríguez-Iturbe (2002).

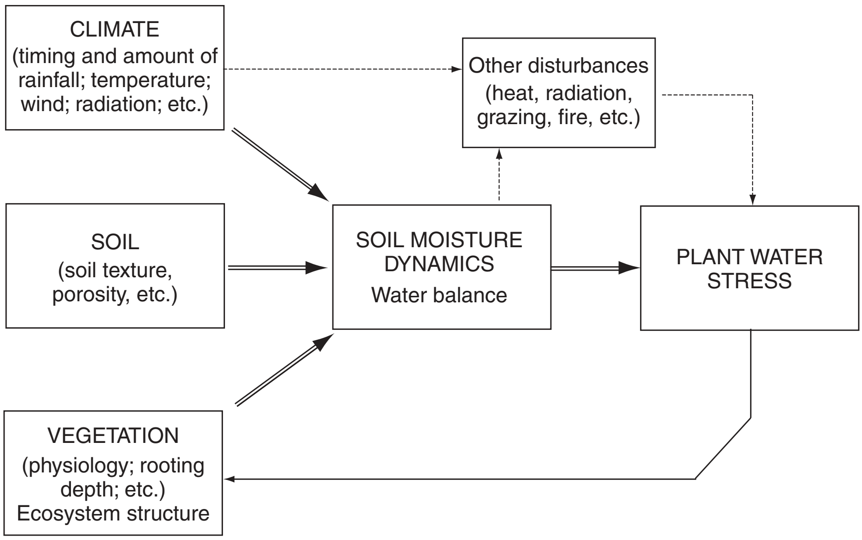

Figure 1.6 First and main level of description of the climate–soil–vegetation system. Climate and soil characteristics may be considered as external forcing components while soil moisture dynamics pivots the mutual links between the vegetation and water stress. As modified by Porporato and Rodríguez-Iturbe (2002) after Rodríguez-Iturbe et al. (2001a).

will concentrate on the direct action of soil moisture on carbon and nitrogen cycles with a short discussion of the role of feedbacks from plant dynamics.

Finally, a more general level of description is introduced when the system is analyzed at large spatial scales (e.g., continental). Large-scale patterns of vegetation types (and also water stress) induce corresponding patterns of albedo and transpiration characteristics that heavily condition the dynamics of the atmospheric boundary layer and the formation of convective precipitation. Thus the climatic/atmospheric component becomes influenced by the feedbacks induced by the soil–plant system. The climate component is no longer an external forcing and becomes an essential part of the dynamics (e.g., Segal et al., 1988; Eltahir, 1996; Sellers et al., 1997; Porporato et al., 2000; Pielke, 2001). Such a problem, briefly discussed in Chapter 6, connects ecohydrology to hydrometeorology, another important discipline from the family of the hydrologic sciences. The implications of soil–plant–atmosphere interaction involve not only the exchanges of water between the components of the system, but also CO_2 fluxes between ecosystems and the atmosphere and the many feedbacks on the nitrogen cycle (e.g., Siqueira et al., 2000; Dickinson et al., 2002).

1.4 Temporal scales

Although micrometeorology and plant physiology control transpiration and photosynthesis at small temporal scales (e.g., hourly), the soil moisture fluctuations controlling ecological processes and patterns may be studied through a suitable functional representation of the main interactions at the daily time scale, thus avoiding the explicit modeling of the hourly variations in the different parameters (e.g., internal storm structure, evapotranspiration diurnal variations, photosynthesis, etc.). Such a simplification is empirically supported by field and laboratory experiments (see Chapter 2) and may also be justified analytically by upscaling the soil–plant water balance from the hourly to the daily time scale (see Chapter 6).

The uncertainty of both the timing and amount of rainfall has induced vegetation to develop different strategies to respond to water stress and optimize reproduction and productivity (e.g., Noy-Meir, 1973). As a consequence, any effort towards ecohydrological modeling has to take into account the stochastic character of soil moisture dynamics. Accordingly, precipitation input is modeled as a stochastic process interpreted at the daily time scale. For the sake of simplicity, at the beginning (Chapters 2–6), only cases with negligible seasonal and interannual rainfall components are considered. The growing season is thus assumed to be statistically homogeneous: the effects of the initial soil moisture condition are considered to last for a relatively short time and the probability distribution of the soil water content to settle in a state independent of time.

However, steady conditions are not always representative, especially at the beginning of the growing season. For example, the soil moisture initial condition is very different between the savannas of Nylsvley in South Africa and the forests in northwestern United States. At Nylsvley, the growing season from September to April receives 98% of the annual rainfall and is preceded by a warm and dry winter season, which makes initial soil moisture conditions at the start of the growing season practically irrelevant. On the contrary, in northwestern United States a relatively dry growing season is preceded by a wet and cold winter season: these factors, combined with a deep active soil layer, make the initial value of soil moisture storage a commanding factor in water use by plants (see Chapters 3 and 7). As a consequence, the case of Nylsvley is likely to be well represented by the statistically steady-state properties of the soil moisture process, while for the forests of northwestern United States the transient properties of soil moisture dynamics are crucial for an adequate statistical representation of the conditions during the growing season.

In other cases, seasonal components in transpiration and precipitation may have dramatic consequences for plants. For example, in many subtropical climates, rainfall and transpiration are in phase and have highest rates during the growing season, while in Mediterranean climates rainfall, being mostly concentrated during the winter season, is in counterphase with the growing season transpiration. This results in very different seasonal patterns of soil water availability and thus, even if the total annual precipitation and average temperature are the same, in very different vegetation structures. Figure 1.7

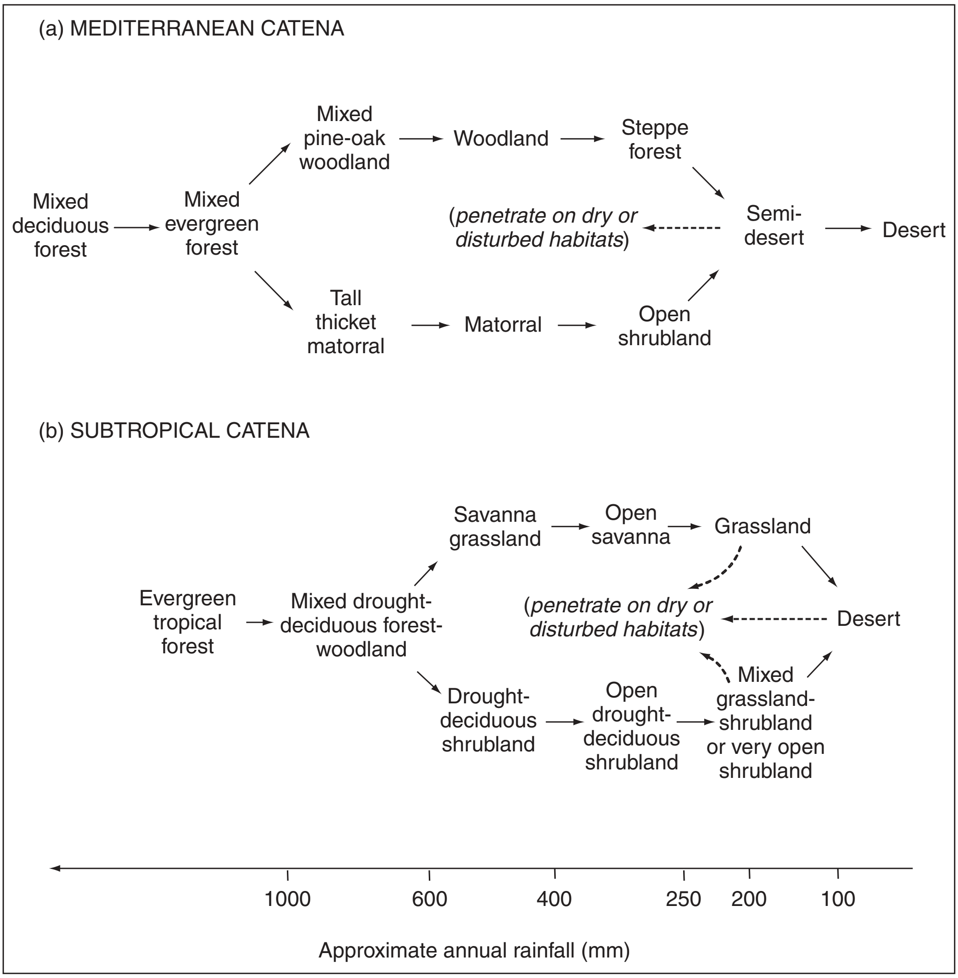

Figure 1.7 Different vegetation catenae (from an arboreal temperate formation to a contracted desert) as an example of specific ecosystem structures resulting from different seasonal patterns of water availability. (a) Mediterranean catena; (b) subtropical catena. As modified by Porporato and Rodríguez-Iturbe (2002) after Shmida and Burgess (1988).

reports the typical vegetation catenae (from an arboreal temperate formation to a contracted desert) for Mediterranean and subtropical climates: in the region between 400 and 250 mm of annual rainfall, for instance, one may find steppe forests and open shrublands in Mediterranean climates, or open savannas and drought-deciduous shrublands in ecosystems with subtropical climates. At longer time scales, interannual fluctuations also become important, superimposing themselves on the daily and seasonal components. Seasonal and interannual hydrologic fluctuations will be the subject of Chapters 8 and 11.

1.5 Spatial dimensions

Spatial scales are extremely important in the analysis of the climate–soil–vegetation system. At the local scale, the differences in the active soil depth produce a variety of different responses to the rainfall input, with clear implications for plant water stress (Noy-Meir, 1973; Porporato et al., 2001). Wherever relevant topographic features are present, the lateral fluxes may be an important factor for the spatial distribution of soil moisture and its temporal evolution; slope and aspect also control the local net radiation input and, consequently, soil moisture dynamics. Unfortunately, due to the spatial components, the mathematical analysis is considerably more difficult and analytical solutions are often replaced by numerical analyses (e.g., Chapter 9). Brought to the entire catchment scale, this line of research will hopefully blend in a natural manner the interaction among the statistical fluctuations in precipitation and soil moisture, the statistical geometry of the river basins, and the structure of vegetation.

Much of the analysis in this book refers to a spatial scale of a few meters, characteristic of the domain of a typical plant where vegetation and soil are assumed to be homogeneous (plot scale). The commanding features of the spatial scales arise from the spatial variability of the soil and vegetation condition. Soil composition and soil properties, which are very important for the resulting soil moisture dynamics, generally vary at much smaller spatial scales than the rate of arrival of storms during the growing season or the average depth of the rainfall events.

Apart from the analyses of Chapter 9, which account for the vertical profile of infiltration and root density, the dynamics of soil moisture is modeled at a point for vertically averaged conditions and the vertical dimension is all embedded in the dependence of soil moisture dynamics on the rooting depth. The effect on soil moisture dynamics of lateral fluxes resulting from topographic features is also considered in Chapter 9. As is often the case in arid