

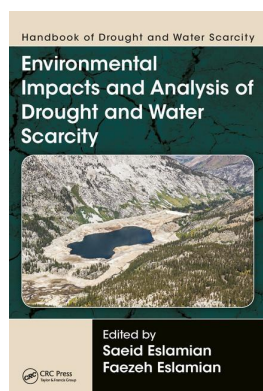
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Environmental Impacts of Drought on Desertification Classification

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3

Environmental Impacts of Drought on Desertification Classification

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Abstract Desertification is an ecological and environmental issue and a slow-developing hazard. Desertification constitutes land degradation in arid, semiarid, and dry subhumid areas. Desertification results from a combination of natural and anthropogenic causes that lead to land degradation. Indeed, there are several factors contributing to desertification, such as climate, geology, soil, hydrology, physiography, biology, and human activities. Moreover, prolonged drought periods also result in soil exposure, erosion, land degradation, and, eventually, desertification. The objective of this chapter is to show a desertification classification scheme that results from drought environmental impacts. This chapter emphasizes on a two-stage methodology for the quantitative classification of severity of desertification over a region starting from drought assessment through the standardized precipitation index, followed by erosion assessment considered based on the Pan-European Soil Erosion Risk Assessment model. At the second stage, mapping of groundwater levels is conducted, which is followed by the water quality component of desertification. Finally, composite mapping of the two stages is produced, leading to the final scheme of desertification severity classification.

3.1 Introduction

An existing definition states that desertification constitutes “land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities,” which has been approved by the *United Nations Conference on Environment and Development*

(UNCED: Chapter 12 of Agenda 21) [31]. However, this is a general definition, which does not focus on the interaction between various factors such as climatic and socioeconomic factors. Needless to say, human activities are occasionally decisive in triggering desertification processes. The predominant land use of drylands is agriculture, specifically pastoralism and subsistence food production. Where, in drylands, arid, semiarid, and dry subhumid areas are considered. Indeed, land degradation results in the reduction or loss of the biological or economic productivity and complexity of rained cropland, irrigated cropland, or range, pasture, forest, and woodland.

Desertification is the outcome of a combination of natural and anthropogenic causes, leading to land degradation. Indeed, there are several factors contributing to desertification, such as climate, geology, soil, hydrology, physiography, biology, and socioeconomic and human activities [34]. Moreover, desertification is intensified due to climate change, since lack or deficit of precipitation is the major driving force and feature of drought and constitutes a serious threat for the protection of certain environments, such as the Mediterranean region. Indeed, it is evident that in arid and semiarid regions, the existing risk of land degradation and desertification creates a vicious circle with climate change and human activity [34]. Specifically, prolonged drought periods result, among others, in soil exposure, erosion, land degradation, and, eventually, desertification. Nevertheless, soil erosion is a natural process that is essential for soil formation. With respect to land degradation, most concerns about erosion are related to accelerated erosion, where the natural rate has been significantly increased by human activity. In fact, soil erosion by water is a widespread problem throughout Europe and other parts of the world.

It is recognized that droughts have several significant impacts, which can be direct and indirect. Direct drought impacts include reduced cropland or forest and rangeland productivity, reduced water levels, increased fire hazards, increased livestock and wildlife mortality rates, and damage to wildlife and fish habitat. The consequences of these direct impacts are considered indirect impacts. Furthermore, drought impacts can be classified based on the affected sector, leading to environmental, economic, or social impacts. In particular, environmental impacts involve the losses that result as a direct consequence of drought; however, they may also involve indirect losses, such as the desertification process or the wildfire damage to plant and animal species. Moreover, several economic impacts affect agriculture and other related sectors. Finally, social impacts are mentioned, which refer to public safety, health, quality of life issues, water use conflicts, and regional inequities in relief and impact distribution.

The desertification phenomenon is distinguished from the classical concept of desert, such as the Kalahari and the Sahara deserts, where meteorological drought constitutes a unique and distinct factor that causes desert conditions independent of other environmental factors. Indeed, in the Mediterranean region, for instance, desertification processes become active and accelerated only when, despite climatological restrictions, there are other soil parameters that lead to critically low limits due to human activities [1]. As a result, the desertification phenomenon is spatially and temporally discontinuous. Nevertheless, desertification affects over 250 million people and, in addition, almost one billion people over 100 countries are at risk. Fighting against desertification is essential for ensuring the long-term productivity of populated drylands. However, past activities to combat desertification have often failed, resulting in the continuation and worsening of land degradation. Specifically, one quarter of earth's land is threatened by desertification, which corresponds to an area of over 3.6 billion hectares. Moreover, since 1990, 6 million hectares of productive land is lost every year due to land degradation. Thus, it is worth mentioning that desertification threatens the livelihoods of one billion people.

The objective of this chapter is to develop a desertification classification methodology, which results from drought environmental impacts. This chapter emphasizes on a two-stage methodology for the quantitative classification of desertification severity over a region. Specifically, physical desertification is considered, starting from drought assessment by employing widely used indices, and then, erosion assessment is considered based on modelling of the soil loss function. The development of composite maps of these two factors over the examined region leads to quantitative classification, which constitutes the first stage of the quantitative classification of desertification severity. At the second stage, mapping

of groundwater (GW) levels is considered based on groundwater modelling. This is followed by the consideration of the chemical desertification component through the analysis and mapping of water quality field data and measurements. Then, composite mapping of stage 2 factors is added to the produced mapping of stage 1, leading to the final scheme of desertification severity classification. This chapter is organized as follows: [Section 3.2](#) briefly describes drought concepts, types, quantification, indices, and features. [Section 3.3](#) presents a conceptual and comprehensive description of desertification, including causes, factors, stages, assessment methods, and mitigation. Finally, [Section 3.4](#) presents the two-stage methodology for the quantitative classification of desertification severity.

3.2 Drought Quantification and Assessment

It is recognized that there is an absence of a precise and universally accepted definition of drought, because there is a wide variety of sectors affected by drought as well as an increasing water demand for different uses and its diverse spatial and temporal distribution [13]. Definitions of drought are usually region and application or impact specific. Specifically, droughts are regional in extent and each region has specific climatic characteristics. In addition, definitions of drought need to be application specific, since drought impacts vary between sectors. Moreover, by considering drought as a hazard, there is a tendency to define and classify droughts into different types. Indeed, definitions of drought can be classified as either conceptual or operational. In particular, conceptual definitions are general and help the public to understand the concept of drought. On the other hand, operational definitions contribute to the identification of the severity and duration of drought and are more useful in drought assessment and planning.

3.2.1 Drought Types and Quantification

In the international literature, three operational definitions of drought are considered, namely, meteorological or climatological, agricultural or agrometeorological, and hydrological [6,13,35]. In addition, there is a fourth type of drought, the socioeconomic impacts of drought, which is also considered. All droughts begin with a deficiency of precipitation in a region over a period of time. These early stages of accumulated departure of precipitation from normal or expected are usually considered as meteorological drought [27]. A continuation of these dry conditions over a longer period of time, sometimes in association with above-normal temperatures, high winds, and low relative humidity, quickly results in impacts in the agricultural and hydrological sectors. Specifically, with the exception of meteorological drought, the other types of droughts, such as agricultural and hydrological, emphasize on the human or social aspects of drought, in terms of the interaction between the natural characteristics of meteorological drought and human activities that depend on precipitation, to provide adequate water supplies to meet societal and environmental demands [16]. Needless to say, the relationship between the different drought types is complex. A brief description of the previously mentioned drought types is as follows:

Meteorological or climatological drought is a region-specific natural event, due to the regional nature of atmospheric phenomena, resulting from multiple causes. It is defined as the degree of dryness specified by deficiencies of precipitation and the dry period duration. Meteorological drought is generally characterized by a precipitation anomaly, being lower than average in a region for some period of time, and by prolonged and abnormal moisture deficiency.

Agricultural or agrometeorological drought refers to the agricultural impacts resulting from deficiencies in the water availability for agricultural use. Indeed, agricultural drought is described in terms of crop failure and occurs when soil moisture is depleted so that crop yield is reduced considerably. Specifically, agricultural drought is defined by the availability of soil water to support crop and forage growth and there is no direct relationship between precipitation and infiltration of precipitation into the soil. In fact, infiltration depends on antecedent moisture conditions, soil type, slope, and precipitation intensity. Soils with low water holding capacity are typical to drought-prone areas, which are more vulnerable to agricultural drought.

Hydrological drought is normally defined by the departure of surface and subsurface water from some average conditions over a long time period resulting from meteorological drought. Hydrological drought is considered to be a period during which the actual water supply, either surface water or groundwater, is less than the minimum water supply necessary for normal operations in a particular region (watershed). Like agricultural drought, there is no direct relationship between precipitation amounts and the status of surface and subsurface water supplies. There is also significant time lag between departures of precipitation and the appearance of these deficiencies in surface and subsurface components of the hydrological system [27].

Finally, *socioeconomic* drought is defined in terms of loss from an average or expected return and can be measured by both social and economic indicators [22]. Indeed, socioeconomic drought refers to the gap between supply and demand of economic goods brought on by the three other types of droughts described before, such as water, food, raw materials, transportation, and hydroelectric power, as a result of a weather-related shortfall in water supply. Socioeconomic drought is different from other types of droughts, since its occurrence depends on the spatiotemporal processes of supply and demand.

As already mentioned, quantification of drought is accomplished through drought indicators, which are variables describing drought features, such as magnitude, duration, severity, periodicity, areal extent, onset, and end time [3]. Primary data for meteorological, agricultural, or hydrological drought indicators are climate variables, such as temperature and precipitation, streamflows, soil moisture, reservoir storage, groundwater levels, snowpack, and vegetation. Data analysis, interpretation, and aggregation lead to drought indicators and/or indices. There are several review studies on the use of drought indicators and indices based on conventional and/or remotely sensed data [13,15,23]. There are questions about the scientific and operational validity of an index, that is, how each indicator is combined and weighted in the index and how an index value is related to geophysical and statistical characteristics of drought [30]. Nevertheless, drought indices can provide ease of implementation and are extensively used in drought quantification and assessment [19,21].

In evaluating the overall utility of indices, a set of weighted decision criteria are usually assigned to each index, which are based on desirable properties of each index, namely, robustness, tractability, transparency, sophistication, expendability, and dimensionality [16]. It is clear that the previous criteria weights, which reflect the relative importance of the evaluation criteria, are difficult to be precisely justified. The list may be expanded or condensed, but the previous criteria provide a reasonable framework for the evaluation of drought indices without excessive complication.

3.2.2 Drought Features and Assessment

For assessing and monitoring droughts, several drought features are usually detected. Specifically, conventional and/or remote sensing data and methods can be used to delineate the spatial and temporal variability of several drought features in quantitative terms [4–6]. A description of some key features follows. *Severity* or intensity of drought is defined as escalation of the phenomenon into classes from mild, moderate, severe, to extreme. The severity is usually determined through drought indicators and indices, which include the previously mentioned classes. The regions affected by severe drought evolve gradually, and there is a seasonal and annual shift of the so-called epicenter, which is the area of maximum severity. *Periodicity* is considered the recurrence interval of drought. *Duration* of a drought episode is defined as the time interval from the start and end time, usually in months. Since drought is a complex phenomenon, the assessment of start and end time is a complicated technical subject. *Onset* is the beginning of a drought, which is determined by the occurrence of a drought episode. The beginning of a drought is assessed through indicators or indices reaching a certain threshold value. *End time* of a drought episode signifies the termination of drought, based again on threshold values of indicators or indices. It is often difficult to determine the onset and the ending of a drought and on what criteria

these determinations should be made. *Areal extent* of drought is considered the spatial coverage of the phenomenon as quantified in classes by indicators or indices. Areal extent varies in time, and remote sensing has contributed significantly in the delineation of this parameter by counting the number of pixels in each class. From a planning perspective, the spatial characteristics of drought may have serious impacts to several sectors of the economy, such as agriculture, energy, transportation, health, recreation, and tourism.

It is accepted that drought indices can be easily implemented and are extensively used in drought quantification, assessment, and monitoring. Indeed, traditional methods of drought assessment and monitoring rely on rainfall data. Although precipitation is the basis of many drought indicators, many other indicators are also significant in the assessment and monitoring of drought severity. Moreover, it is recognized that remote sensing has gradually become an important tool for the detection of the spatial and temporal distribution and characteristics of drought at different scales. In summary, it is best to consider multiple indicators to verify the existence and severity of drought.

3.3 Desertification Hazard

Desertification is an ecological and environmental issue and a slow-developing environmental hazard. As already defined, desertification constitutes land degradation in arid, semiarid, and dry subhumid areas. Moreover, it is significant and useful to identify the high-risk areas in order to proceed in a quantitative classification of desertification. Indeed, the characteristics of such areas include low annual rainfall depth, high annual potential evapotranspiration (PET), uneven precipitation distribution in space and time, increased intensity and high corrosion of rainfall, high soil moisture deficit, and high temperatures during the vegetative growing season. Furthermore, desertification can be characterized as physical or chemical, depending on the processes involved. Specifically, physical degradation occurs on sloping land and is very extensive, where the dominant physical process is accelerated soil erosion, which occurs on marginal lands that have lost more than 60% of vegetative cover and are located within the semiarid and dry subhumid zones. In addition, the dominant process of chemical desertification is secondary salinization of soils through irrational water management in irrigated lands. The main causes are irrigation with waters containing soluble salts exceeding critical thresholds, irrigation schemes failing to meet leaching requirement or raising saline groundwater tables, and overpumping of coastal aquifers causing the intrusion of seawater. Chemical desertification is localized in some alluvial plains and it is not very extensive in the Mediterranean region; however, it affects valuable land.

A brief description of desertification hazard is presented starting from a presentation of the causes and factors contributing to desertification, and then assessment methods and modelling efforts are described. This is followed by a presentation of the stages that lead to desertification, and, finally, mitigation measures to combat desertification are described.

3.3.1 Causes and Factors of Desertification

As already mentioned, the causes of desertification can be either natural or anthropogenic. Specifically, natural causes include dry climate, geomorphology of soil erosion processes, quantitative and qualitative alterations of the water balance, and the historical aspects of a region. On the other hand, anthropogenic causes include urbanization, overexploitation and forest fires, overexploitation of surface and underground resources, inappropriate land use changes in forest fires, agricultural intensification, overgrazing, inadequate forest and agricultural management practices, urban and industrial expansion, tourism, and socioeconomic factors.

The identification of the factors contributing to desertification is a complex process, since the factors pointed out as the main originators of land degradation are most varied, such as climate change, deforestation, predatory exploitation, extensive cultivation, industrialization, and urbanization [25]. There are many factors that trigger desertification, including the unpredictable effects of drought,

fragile soils and geological erosion, livestock pressures, nutrient mining, population increase, landlessness and an inequitable distribution of resources, poor infrastructure and market access, neglect by policy makers and agricultural and environmental research systems, and the failure of markets to reward the supply of environmental services. The factors of desertification can be categorized and the perspective categories are briefly described in the succeeding text.

3.3.1.1 Climate

Climate and desertification interact at a variety of scales. Indeed, climate affects the desertification processes through its impact on dryland soils and vegetation, as well as on hydrological cycle in drylands [10]. Unlike the organically rich soils of more humid regions, dryland soils often have low organic matter content and are frequently saline and/or alkaline. Moreover, desertification affects global climate change through soil and vegetation losses. Specifically, dryland soils contain a lot of carbon, which could be released into the atmosphere as a result of desertification, with significant consequences for the global climate system. Indeed, the effect of global climate change on desertification is complex and not yet sufficiently understood. At first, higher temperatures can have a negative impact through increased loss of water from soil and reduced rainfall in drylands. On the other hand, an increase in carbon dioxide in the atmosphere can boost plant growth for certain species. In addition, although climate change may increase aridity and desertification risk in many areas, the consequent effects of biodiversity loss on desertification are difficult to predict [31]. Moreover, arid, semiarid, and dry subhumid areas, other than polar and subpolar regions, are defined as the areas with the 0.03–0.65 ratio of annual precipitation (P) to PET, which is known as the aridity index (Table 3.1). In general, when the ratio is lower than 0.03, there is always desertification, whereas when the ratio is higher than 0.65, there is no desertification.

3.3.1.2 Geology and Soils

The properties of rocks can influence the desertification process due to their permeability, the rate of weathering of rocks, and soil corrosion. These rocks are limestones and marls of hilly land. In these rocks, the soil is shallow and sensitive to drought. Other rocks, which form soils slowly and have coarse composition, are the acid fumed and the volcanic rocks.

Soil is an open natural system, interacting with the environment and resulting in strong impact on that. Such a system faces continuous changes of various rates based on the intensity of inputs and outputs to the environment. Under natural conditions, the changes are slow and there is a balance between the rates of soil formation and the rates of changes and losses. As a result, there is sustainability in the ecosystem. Nevertheless, soil is a nonrenewable resource, which can be easily destroyed, and faces continuously increasing pressure. Rational management of soil resources may sustain or even improve its productive ability over a long time; otherwise, it may take even centuries to be re-created through edaphogenesis processes. Moreover, land degradation is characterized by changes in the physical, chemical, and biological soil properties, which lead to erosion, loss of its productivity ability, and, most times,

TABLE 3.1 Dryland Categories

Aridity Index: P/PET	Rainfall (mm)	Classification
(PET > P)		Desert climate
<0.03	<200	Hyperarid
0.03–<0.20	<200 (winter) <400 (summer)	Arid
0.20–<0.50	200–500 (winter) 400–600 (summer)	Semiarid
0.50–<0.65	500–700 (winter) 600–800 (summer)	Dry subhumid
>0.65		No desertification

desertification [33]. Indeed, irrational land use due to human intervention leads to land degradation and desertification, which is directly related to low productivity of land and the exhaustion of available water resources.

It is accepted that desertification proceeds in a certain landscape, when the soil is not able to provide the plants with rooting space, water, and nutrients. In the semiarid and subhumid zones, the land becomes irreversibly desertified when the rootable soil depth is not capable of sustaining a certain minimum vegetation cover. Moreover, there are cases that desertification proceeds even on deep soils, when their water balance is not capable of meeting the needs of plants. Extensive studies in several European research projects, such as DESIRE, DESRTLINKS, and MEDALUS, have shown that soil parameters greatly affecting desertification are parent material, soil depth, slope gradient, slope aspect, soil texture, and the amount of rock fragments on the soil surface. These parameters are related to water availability to plants and to soil erosion resistance. Indeed, soil characteristics, which affect desertification rate and processes and are considered as desertification risk indicators, are soil depth, soil texture, soil moisture, soil fertility, organic matter, surface infiltration, hydraulic conductivity, and field capacity. In particular, the soil performance is connected to desertification through soil formation rate, water holding capacity, plant nutrient availability, and soil erodibility. Moreover, physiography affects significantly the three desertification processes, which favor the previously presented features, namely, erosion, salinity, and aridity. In addition, desertification depends on slope gradient, aspect, and shape of land. Specifically, two equations are presented, soil loss rate (Equation 3.1) and erosion (Equation 3.2), respectively, as follows:

$$E1 = cS^a \quad (3.1)$$

$$E2 = bL^m \quad (3.2)$$

where

E1 is the soil loss

S is the slope gradient

E2 is the erosion

L is the slope length

c, a, b, m are the empirical coefficients

By removing the most fertile topsoil, erosion reduces soil productivity and, where soils are shallow, may lead to a permanent loss of natural farmland. Indeed, erosion rate is very sensitive to both climate and land use. For example, the Mediterranean region is mostly vulnerable to erosion, because it is subject to long dry periods followed by heavy bursts of erosive rain, falling on steep slopes with fragile soils [3]. On the other hand, in northwest Europe, soil erosion is not yet a serious problem, since rain mainly falls on gentle slopes, evenly distributed throughout the year, and affects less extensive areas than in southern Europe.

3.3.1.3 Hydrology and Water Resources

The land phase of the hydrological cycle signifies the driving force, which may have impacts and lead to desertification. This process extends until the available water supplies are insufficient to cover the requirements of living organisms, such as plants and animals. Nevertheless, there are water losses and abstractions, such as surface runoff, infiltration, deep percolation to groundwater, and groundwater flow to sea, which are very critical for desertification, especially in vulnerable and sensitive areas [9]. Moreover, water losses may occur from sparse vegetation cover, environmental pollution, urban and industrial demand, permeability of limestone rocks, and groundwater exploitation and sedimentation. A possible solution for preventing these areas from desertification may be irrigation, which replenishes the soil moisture, resulting in plant growth.

Water resources are under severe physical, social, economic, and environmental stresses, compounding to the water uses. Moreover, the need for agriculture intensification to meet high production costs, the lack of drainage systems, and the use of poor water quality, for example, seawater intrusion, are in many cases responsible for soil degradation resulting from salinization, water logging, alkalization, and soil erosion. Soil salinization, resulting from poor water quality, is one of the key processes that could lead to desertification. Indeed, in the plain areas along the coast, soil salinization is a growing problem all over the world and affects millions of hectares in Europe. In such cases, agriculture plays a major role by causing high water consumption and water chemical degradation, although at the same time the economic sector faces the strongest impacts.

One main reason for the increase of the amounts of salts in aquifers is the seawater intrusion due to overexploitation, which results from increasing water demands for multiple uses. As already mentioned, the use of poor water quality for irrigation under certain soil and climatic conditions leads to soil salinization. Moreover, increasing salt levels in the topsoil layers can affect plant growth and productivity. Indeed, high concentrations of various salts, for example, sodium chloride and magnesium and calcium sulfates and bicarbonates, affect plant growth both directly by their toxicity and indirectly by increasing osmotic potential and lowering root water uptake. Furthermore, in dry climates, continuous salt accumulation could lead to desertification, whereas in humid or subhumid climates, moderate or severe salinization may occur periodically.

3.3.1.4 Biology

The most dominant biotic land component that affects desertification is the vegetative cover of land, which is also the best possible indicator for desertification. When persistent changes in vegetation cover are observed and barren areas increase continuously, this signifies a desertification trend. However, this indicator should be treated cautiously, since seasonality and rainfall (P) variability in drylands also result in increased variability of vegetation cover. Moreover, vegetation cover depends on the existing relationships between climate, soil, and vegetation in an area. Indeed, areas with annual precipitation $P < 280$ mm and high evapotranspiration rate suffer reduction of water availability, gradually resulting in bare soil land. In addition, areas with rainfed crops (Table 3.2) [10] are very sensitive to erosion and desertification, since the reduced protection by vegetation cover cannot prevent effective rainfall intensity at the ground surface.

Many studies have demonstrated that in a wide range of environments, both runoff and sediment loss decrease exponentially with an increasing percentage of vegetation cover [8]. Forest vegetation reduces significantly the summer soil surface temperatures and it is necessary for the regeneration of many forest species in the Mediterranean. A vegetation cover of the order of 45%–50% is considered as a critical value, since above this value soils are adequately protected from raindrop impact and soil erosion is significantly reduced [11]. Moreover, both runoff and sediment loss are greatly affected by plant cover reducing raindrop impact. Furthermore, as already mentioned, plant cover significantly prevents the increase of the summer soil surface temperatures and soil water conservation. Plant cover is a crucial indicator of land desertification, especially in areas affected by water stress. In addition, climate greatly affects plant cover. Indeed, high annual air temperatures promote low plant cover due to high evapotranspiration demands. Furthermore, low amounts of annual rainfall negatively affect plant cover.

TABLE 3.2 Typical Rainfed Crops Grown in Drylands

Classification	Growing Season (Days)	Typical Crops
Hyperarid	0	No crop, no pasture
Arid	1–59	No crops, marginal pasture
Semiarid	60–119	Bulrush millet, sorghum, sesame
Dry subhumid	120–179	Maize, beans, groundnut, peas, barley, wheat

In addition, high rain seasonality indices usually promote low plant cover percentages. Furthermore, soil depth, soil texture, and exposure of rock outcrops greatly affect soil water storage capacity and, therefore, plant growth and plant cover under semiarid or arid climatic conditions.

3.3.1.5 Human Activities

The main human factors are considered to be of socioeconomic nature. One factor is the population growth and the continuous increase in water consumption leading also to environmental pollution. Intensification of agriculture through human intervention is another factor, since overexploitation of plant biomass and irrational cultivation of hilly lands result in soil erosion. Moreover, deforestation and reduction of vegetative cover due to forest fires, overgrazing of sensitive areas, land abandonment, and irrational land development and tourism lead to land degradation. In addition, increase of surface runoff to the sea, due to deforestation and overexploitation of water resources, leads to a reduction of the available resources, resulting in salinization of groundwater aquifers and intrusion of seawater in coastal aquifers. Furthermore, ineffective irrigation planning results in redundancy and losses of irrigated water, leading to soil salinity. Needless to say, problems of water scarcity, groundwater depletion, soil erosion, and salinization have all been recognized as outcomes of policy and institutional failures. In summary, the human causes of desertification are not fully understood. Changing paradigms and varying views among researchers mean that there is no consensus yet on how human factors affect desertification [7].

Summarizing this section, according to [12], a limited number of recurrent core variables, of which the most prominent are climatic and economic factors, institutions, national policies, population growth, and remote influences, drive desertification. These factors give rise to cropland expansion, overgrazing, and infrastructure extension. For each location, a set of causal factors, in combination with feedback mechanisms and regional land use, make up specific pathways of land change that could trigger desertification.

3.3.2 Simulation and Modeling

At the global level, Europe is considered the largest area of drylands susceptible to desertification. Indeed, the European Commission has recognized desertification as a major problem in the Mediterranean Europe and has supported research on its causes, impacts, spatial extent, and mitigation. Interdisciplinary, multiscaling, and multilevel integrated projects have been conducted and still continue, such as MEDALUS I, II, and III; EFEDA; and DEMON. There is a large range of methodologies and modelling efforts that have been implemented within research activities related to desertification. Such methodologies include development of numerical models for future climatic scenarios; simulation of the dynamics of the atmosphere, oceans, and energy exchange between atmosphere–continent and atmosphere–ocean; short-term forecasting; prediction of long-term changes in climatic parameters under specific conditions, such as changes in land use and emission of greenhouse gases; use of climatic scenarios to understand future desertification conditions; simulation of climate variability and extreme events with emphasis on small-scale effects; assessment of topography and geomorphology influence on high-resolution downscaling methods; and use of multiple and composite indices to evaluate desertification conditions in areas with large water deficits ($PET > P$).

Existing desertification assessment and monitoring methods are also considered that incorporate geographical information systems and remote sensing techniques, spatial modelling of the desertification severity risk (DSR) in sensitive areas, production of maps representing the main processes causing desertification, analysis of satellite imagery during drought severity assessment, and development of desertification classification schemes in sensitive areas. With nearly one in six people worldwide presently at risk from the impacts of land degradation, much research effort and work remains to be conducted in order to cover current needs and trends. Such efforts, among others, include monitoring and preventing desertification, improving the knowledge about desertification processes and understanding

causal interactions and environmental implications, developing institutional evaluation schemes and feedback mechanisms, and distributing scientific knowledge through several technological schemes and platforms.

Needless to say, from these assessment studies, it is evident that there is a need for high-quality data. Many dryland areas are subject to degradation processes, such as wind and water erosion. Hence, an observation of wind erosion in a certain area is not sufficient to conclude that the area is experiencing desertification. Only when the frequency of dust storms rises and the magnitude of the storms increases is there a clear indication of ongoing land degradation. A different indicator that has been used to identify land degradation is crop yield data. However, decreasing yields could have been caused by a lack of fertilizer use, and thus the yield data are not necessarily indicative of desertification. Moreover, timing of the vegetation observations is of crucial importance and should be conducted during the growth period when vegetation cover is at its maximum. Furthermore, remote sensing data can be used for the assessment of land use, land cover, landscape features, soil characteristics, and land degradation features. Other features that can be detected from satellite images include salinization patterns in irrigation schemes; overgrazing features, such as low-cover grasslands around animal paths; large water erosion patterns over large areas; and burned areas or areas subject to bushfires.

3.3.3 Processes Leading to Desertification

Following the causes and factors that contribute to drought and furthermore to desertification, the stages and the processes that lead to desertification are briefly presented.

3.3.3.1 Stage 1: Soil Degradation

The main issue is the reduction of the vegetation coverage over an area, which has the result that the raindrops falling on the ground reach the surface. In addition, soil erosion is a significant process of land degradation and, consequently, desertification. The European Mediterranean region, characterized by high rainfall erosivity and high soil erodibility, is generally susceptible to soil erosion. Several studies have reported the important role of vegetation cover and land use management to the variation in runoff and sediment yields. Specifically, the key limit of plant cover (40%) has been identified [11], under which accelerated soil erosion occurs. It is also found [20] that the lowest rates of annual runoff and sediment loss occurred in hilly areas cultivated with olives, and it also highlighted the significant role of the annual plant understory vegetation in limiting soil loss in moderately steep olive orchards. Indeed, recent efforts for quantifying the desertification phenomenon have been carried out [2] illustrating that soils with permanent vegetation cover generate soil sediment losses by at least one order of magnitude lower than those on arable land.

According to the United Nations Environment Program [32], soil salinization is one of the main degradation processes in arid zones that can lead to land desertification. Salinization is included among the eight major threats to soil quality and sustainability in Europe [24]. The concentration of salts in the root zone increases the osmotic potential of soil solution [29] and consequently the normal absorption of water and nutrients. Some specific ions, such as sodium, chlorine, and boron, have independent toxic effects on plants; therefore, soil salinity, except osmotic stress, nutrient (N, Ca, K, P, Fe, Zn) deficiency, and oxidative stress on plants, imposes ion toxicity [28].

As already stated, vegetation is a crucial factor, which affects soils in all its dynamics, including erosion control, water redistribution over and within the soil, and the microbial activity. Surface water runoff is greatly controlled by vegetation, which can be readily altered in hilly areas depending on climatic conditions and the period of the year. Moreover, the microbial activity affects water infiltration and soil aggregation, especially in the surface soil horizon. Extensive Mediterranean areas cultivated with rainfed crops, such as cereals, vines, almonds, and olives, are mainly confined to hilly lands with shallow soils very sensitive to erosion [20]. These areas become vulnerable to erosion and desertification,

due to the decreased protection effect of the vegetation cover from raindrop impact during heavy rains. Specifically, soil erosion measurements conducted along the Mediterranean Europe and Portugal during the execution of the EU research projects MEDALUS have shown that under the existing land management practices, the land that uses vines generates the highest amount of runoff and sediment loss, followed by eucalyptus, cereals, shrubland, and olive groves under minimum tillage in a decreasing rate [20]. Moreover, olives present a particularly high adaptation and resistance to long-term droughts and under seminatural conditions support a remarkable diversity of flora and fauna, even higher than some natural ecosystems, protecting hilly areas from erosion and desertification.

3.3.3.2 Stage 2: Reduction of the Organic Matter and Deterioration of the Soil Structure

Organic matter is the connecting factor between the soil particles. The reduction and, eventually, lack of organic matter may cause the weakening of the soil agglomerates, resulting in the reduction of the biomass production. Soil salinization affects mainly plain areas with poor drainage conditions and especially coastal areas. Except the important climate characteristics of low annual rainfall (lower than 650 mm) and high aridity indices, human actions related to water resources exploitation, such as groundwater exploitation, water consumption/water demands, irrigation percentage of arable land, and water scarcity, are greatly affecting soil salinization in areas prone to desertification. Areas of low water availability accompanied by overexploitation of groundwater and surface water resources are more vulnerable to soil salinization. Furthermore, under high rates of water consumption/water demands, soil salinization is more likely to occur. Areas characterized by high water scarcity, in terms of water consumption per sector, are more vulnerable to soil salinization and land desertification [14]. Furthermore, soil salinization and desertification can be affected by soil water storage capacity. Soils of high water storage capacity are more vulnerable to soil salinization. Soil water storage capacity is related to various soil properties, such as soil texture and soil porosity; therefore, moderately fine and fine-textured soils are more likely to be affected by salinization.

3.3.3.3 Stage 3: Dispersion of the Soil Agglomerates

The soil particles are separated into smaller ones as a result of the falling raindrops. The degradation of the soil surface structure produces a chain of negative effects, starting from the reduction of biomass production and the subsequent loss of a significant amount of water for plants. Specifically, water stress can be considered as an important process of desertification in areas with high rainfall seasonality. Rainfall seasonality is related to the distribution of rainfall during a normal year. An irregular distribution of rainfall, such as the one observed under semiarid climatic conditions with most of the rainfall occurring during the period from October to May, enhances water stress. Human activities, such as increasing rates of groundwater exploitation, promote water stress in the growing plants. Furthermore, dry areas, subjected to high tourism changes or to high population density, are more vulnerable to desertification, since urban water consumption increases at the expense of water used for plant growth.

3.3.3.4 Stage 4: Runoff and Sediment Transfer

This process depends basically on rainfall, but it can also occur due to the wind. With respect to rainfall, the process can lead to surface runoff, as expected. In addition, gradient erosion may also be observed after the rainfall. Indeed, erosion can result in the reduction of the biomass production and the decrease of the available depth in the root zone, as there is depletion of the organic matter and the nutrients. Moreover, studies carried out during the execution of the EU research project DESIRE have shown that 12 indicators have been defined as the most important affecting desertification risk in field sites, where water stress has been recognized as the most important degradation process. The defined indicators are related to climate, soil, water and water use, vegetation, land use, fires, water runoff, land management, tourism, and social and institutional characteristics. The most important indicator related to soils affecting water stress and desertification risk is slope gradient. Under high slope gradients (greater than 25%),

the growing plants are subjected to higher water stress, since surface water runoff is expected to be higher. In addition, under high rates of deforestation or fire frequency, the growing plants are mainly removed, reducing water demands and water stress risk. Water stress is negatively related to soil erosion control measures. If no or low soil erosion control measures are undertaken, then water stress and desertification risk are high. Tourism change is positively related to water stress. Areas under high tourism change (higher than 5%—number of overnight stays in a specific destination in one year averaged by overnight stays in the last 10 years) are more vulnerable to water stress, since urban water consumption increases in charge of water used for plant growth. The same trends with tourism change are found for the indicator population density. Finally, if existing policies on environmental protection are implemented, water stress and desertification risk are diminished.

3.3.3.5 Stage 5: Soil Degradation and Desertification

Reduction of the soil volume and decrease of the soil moisture to the extent that any living form of organism, which is useful for the human and its environment, can survive. Moreover, water scarcity, by definition, means diminishing resources, such as due to climate change, and/or pressure on the supply of available resources from an increasing demand. The water consumption per capita includes the total demands for drinking water, process water, irrigation water, and cooling water by all economic sectors, expressed in cubic meters per year per capita. The World Health Organization uses the level of 1000–2000 m³/person/year to identify risk on water scarcity. When these values drop below 1000 m³/person/year, then areas are considered as experiencing water scarcity. Water scarcity is especially an important indicator for assessing desertification risk in areas where the main cause of land degradation is water stress and soil salinization. Areas under high water scarcity are subjected to higher desertification risk.

3.3.4 Mitigation of Desertification

Desertification must be considered as a global problem and requires direct actions and measures. An integrated land use plan, alternative systems for the exploitation of natural resources, rational use and management of water resources, protection from soil erosion, and forest protection constitute some of the necessary actions. Needless to say, mitigation must be effective even from the first stage of desertification. Indeed, the prevention and choice of solutions for the problem of land degradation, which leads to desertification, must depend on the proper identification of the processes involved and on an accurate analysis, diagnosis, and understanding of the causes and potential effects at specific areas.

Integrated methodologies for land and water management are key measures for desertification prevention. All measures that protect soils from erosion, salinization, and other forms of soil degradation effectively prevent desertification. Moreover, sustainable land use can address human activities, such as overgrazing, overexploitation of plants, and unsustainable irrigation practices, that intensify dryland vulnerability. Management strategies include measures to spread the pressures of human activities, such as rotational use of rangelands and well sites, stocking rates matched to the carrying capacity of ecosystems, and diverse species composition. Nevertheless, improved water management practices can enhance water-related services, which may include use of traditional water-harvesting techniques, water storage, and diverse soil and water conservation measures. Maintaining management practices for water capture during intensive rainfall episodes also helps to prevent surface runoff from carrying away the thin, fertile, moisture-holding topsoil. In addition, improving groundwater recharge through soil–water conservation, upstream revegetation, and floodwater spreading can provide reserves of water for use during drought periods. Moreover, protection of vegetative cover can be a major tool for the prevention of desertification. Maintaining vegetative cover to protect soil from wind and water erosion is a key preventive measure against desertification. Properly maintained vegetative cover also prevents loss of ecosystem services during drought episodes. Reduced rainfall may be induced if vegetation cover is lost due to overcultivation, overgrazing, overharvesting of medicinal plants, woodcutting, or mining activities.

3.4 Desertification Classification Methodology

A methodology for quantitative classification of desertification severity is presented. This methodology includes two stages and each stage has several steps. The adopted procedure is briefly presented.

3.4.1 Initial Assessment of Desertification Severity Risk

This section presents the steps of the first stage for the development of the desertification classification methodology. Specifically, this subsection involves the drought severity assessment, the soil degradation assessment, and the initial classification of desertification risk.

3.4.1.1 Drought Severity Assessment

Drought severity assessment is conducted with the use of the standardized precipitation index (SPI) [20], which is based only on precipitation data. The SPI quantifies the precipitation deficit for multiple timescales, such as for 3-, 6-, 9-, and 12-month periods relative to the same months historically [30]. Ideally, at least 20–30 years of serially complete monthly values are needed with 50–60 years (or more) being more optimal and preferred. The historical rainfall data of the station are fitted to a gamma distribution through a process of maximum likelihood estimation of the gamma distribution parameters. A classification system is used to define drought severities (intensities) resulting from the SPI (Table 3.3). The SPI is computed by dividing the difference between the normalized seasonal precipitation and its long-term seasonal mean by standard deviation. A drought event occurs anytime the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. The SPI is flexible and can be calculated for periods from 1 to 72 months, but it is mostly used for periods of 24 months or less. For the current application, a 12-month period is used. Seven classes of SPI are shown in Table 3.3. Geostatistical analysis is used for spatial interpolation to derive digital maps of the examined area for each time step. It is worth mentioning that an international expert workshop at the University of Nebraska (November 8–11, 2009) announced via the “Lincoln Declaration on Drought Indices” that the SPI is adopted by WMO and recommended as the drought index to be computed and used globally by the National Meteorological and Hydrological Services as the common meteorological drought index [36]. In quantitative terms, the outcome is digital mapping of SPI values on a pixel basis over the area or watershed under study. There are four drought (D) classes (negative SPI values) (D_i , $i = 1-4$) (Table 3.3), namely, class 1, mild dry (-0.50 to -0.99); class 2, moderately dry (-1.0 to -1.49); class 3, severely dry (-1.5 to -1.99); and class 4, extremely dry (less than -2.0). There is also the near-normal class (-0.49 to $+0.49$). The ideal spatial resolution is usually 1 km^2 to be compatible with erosion and groundwater, subject to the number of rain gauges.

TABLE 3.3 Standardized Precipitation Index Classification Scale

Standardized Precipitation Index Value	Moisture Level
+2.0 and greater	Extremely wet
+1.5 to 1.99	Very wet
+1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near-normal–mild dry
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

Source: McKee, T.B. et al., The relationship of drought frequency and duration to timescales, Preprints, *Eighth Conference on Applied Climatology*, American Meteorological Society, Anaheim, CA, 1993, pp. 179–184.

3.4.1.2 Soil Degradation Assessment

Assessment of the land degradation in the study area is conducted from the output of the Pan-European Soil Erosion Risk Assessment (PESERA) model [18]. PESERA has been developed by the European Union to replace previous widely used methodologies, such as the universal soil loss equation model, with a model specifically adapted to European conditions. The PESERA model is a physically based and spatially distributed model developed to assess annual soil losses caused by water erosion in Europe by combining the effect of topography, climate, and soil type. The PESERA model consists of three stages: a storage threshold model to convert daily rainfall to daily total overland flow runoff, a power law to estimate sediment transport from runoff and gradient and to interpret sediment transport at the base of the hillside as average erosion loss, and an integration of daily rates over the frequency distribution of daily rainfall to estimate durable average erosion rates. The computations of the three stages of the PESERA model are conducted for each cell within a 1 km grid. As already mentioned, the model can be used to estimate runoff and erosion rates for a single point and shows the effect of land use change. The model repeats these estimates at every $1 \times 1 \text{ km}^2$ in the examined area or watershed. The latest available PESERA model output map provides modeled soil erosion rates in t/ha/year and at a 1 km^2 grid resolution in ARC-grid format. In quantitative terms, to be compatible with SPI mapping, the range of PESERA output values (SE, soil erosion) can be grouped into four classes (SE_i , $i = 1-4$); thus, each pixel in the examined area or watershed is assigned one value from the four classes.

The PESERA model follows the physically based conceptual separation into runoff generation and erosion by the runoff water, recognizing that soil and vegetation properties have a strong impact on both erosion and runoff, respectively. The amount of sediment transported after each rainfall event is estimated as a mean soil loss in t/ha, obtained as a product of terms, which are primarily dependent on climate, vegetation, topography, and soil, given by the following general equation [17]:

$$Y = \frac{S}{L} = kH^2 \frac{\exp\left(-\left(\Theta/r_0H\right)\right)}{L} \sum_{\text{months}} \left[2pr_0R \exp\left(-\frac{h}{r_0}\right) \right] = k\Psi\Omega \quad (3.3)$$

where

- Y is the sediment loss (t/ha)
- k is the soil erodibility
- Ψ is the topographic erosion indicator
- Ω is the bioclimatic erosion indicator
- R is the total monthly rainfall (mm)
- r_0 is the mean rain per rainy day
- h is the runoff threshold
- p is the proportion of runoff above the runoff threshold
- Θ is the flow power erosion threshold
- H is the mean slope relief
- L is the mean slope length

The PESERA model can be used in two dimensions (2D), along a catena (excel form), or in three dimensions (3D) in a watershed, where the database is prepared in a grid format, for example, $100 \text{ m} \times 100 \text{ m}$. At the European Union level, this model is applied for the estimation of soil erosion risk in 3D at 1 km resolution.

3.4.1.3 Initial Classification of Desertification Risk

The raster maps of SPI values (D_i) combined with simulated annual soil loss rates (SE_i) (using the PESERA model) through the overlay analysis, classify the study area based on the desertification risk.

Invention of a classification scheme assigns cells into classes of sensitivity to desertification. Use of statistical sampling techniques for the selection of cells or group of cells at different sensitivity classes is conducted in order to investigate local hydrological conditions, namely, groundwater levels and water chemistry, focusing on water salinity as an indicator of potential soil salinization and desertification. Then, assessment of hydrological conditions during summer months is considered, when the water deficit is the highest, to represent a “worst-case” desertification risk scenario.

3.4.2 Assessment of Critical Areas to Desertification

This section includes the steps of the second stage for the development of the methodology for the quantitative classification of desertification severity. In particular, this subsection involves the assessment of groundwater levels, the water chemical analysis, the spatial data analysis, and the quantitative classification of desertification risk.

3.4.2.1 Assessment of Groundwater Levels

In order to assess the optimum extracted volume of water, a groundwater modelling system can be used. This system consists of a series of interlinked models for the simulation of the water resources of a watershed, possibly including a lake or reservoir [26], namely, a hydrological model, such as UTHBAL; a lake-aquifer model, such as LAK3; a reservoir operation model, such as UTHRL; and a groundwater model, such as MODFLOW. The models are linked to each other according to the following scheme: The UTHBAL model computes the basin surface runoff and groundwater recharge and passes the first variable to UTHRL and the second one to MODFLOW, respectively. Then, the UTHRL model balances the inflows and outflows of the reservoir and passes the inflows, evapotranspiration, and water withdrawals of the reservoir to the LAK3 model. Finally, the LAK3 model computes the reservoir seepage to the MODFLOW model. The modelling system is calibrated for the historical period against observed runoff and groundwater hydraulic heads. An optimization tool is also used for the aquifer’s pumping optimization [26]. Moreover, the impact of climate change on precipitation and temperature can be assessed. The size of the phreatic aquifer of the lake or reservoir is also assessed, and for simulation purposes, it is discretized into an orthogonal grid consisting of several cells, usually with a grid spacing of $200 \times 200 \text{ m}^2$ and a one-layer aquifer. Groundwater recharge data are obtained by the UTHBAL model, and the water demand for irrigation is mapped over the area creating irrigated zones. The depth of boreholes operating for the irrigation of crops in the selected cells is used as an indicator of groundwater levels. A database of the borehole coordinates and depth values is created, and groundwater level maps are produced. Several interpolation techniques based on geostatistical analysis are examined for the most accurate representation of the spatial variability of groundwater levels in the study area or watershed.

The produced groundwater (GW) level maps are at a 1 km^2 grid resolution to be consistent with the raster data sets of drought severity (D) and soil erosion (SE) rates. Similarly, in quantitative terms, to be compatible with SPI and PESERA mapping, the range of groundwater modelling output values can be grouped into four classes ($\text{GW}_i, i = 1-4$); thus, each pixel in the examined area is assigned one value from the four classes.

3.4.2.2 Water Chemical Analysis

Water sampling and analysis from the boreholes is conducted for pH, conductivity, and bare cations (Na, Mg, Ca, and K). In addition, assessment of the salinity of the irrigation water is considered, which can cause salinization in sensitive soils and consequently desertification. Moreover, determination of the water pH and conductivity is conducted *in situ* using a portable pH and conductivity meter. Furthermore, assessment of the spatial variability of water chemical (WC) concentrations of the analyzed parameters is considered. Finally, maps are produced of the water concentrations, variability at 1 km grid cell. Following the same pattern as in the previous parameters, water chemical (WC) concentrations are classified into four severity classes ($\text{WC}_i, i = 1-4$).

3.4.2.3 Spatial Data Analysis

Multivariate statistical analysis is used, namely, principal component analysis and cluster analysis, to identify sources of variability. Grouping of the raster data sets is conducted using the drought severity, soil loss, and selected hydrological variables data. Moreover, quantitative assessment is considered of the relative importance of the main processes on the severity of desertification in the study area. A combination of the drought (D) severity maps, soil erosion (SE) rates, groundwater (GW) depth, and, if required, water chemical (WC) concentrations maps is conducted using mapping techniques to produce composite mapping and a spatial model for assessing quantitatively the risk of desertification.

3.4.2.4 Quantitative Classification of Desertification Risk

Reclassification of maps into desertification risk classes is conducted using a common classification scheme, which is based on the original raster values of each map. Application of weightings to the map layers is considered depending on the relative importance of each process for causing desertification, using the results of the multivariate analyses. Then, classification of the DSR of the study area is considered and risk classes are defined using standard statistical methods. The resulted quantitative classification scheme of DSR consists of the average composite value on a pixel basis as the sum of the previously mentioned three or four parameters divided by the number of parameters. Specifically, the quantitative scheme takes the following form:

$$(DSR)_i = \left(\frac{1}{N} \right) \sum [(D)_i + (SE)_i + (GW)_i + (WC)_i + \dots + (N)_i], \quad i = 1-4 \quad (3.4)$$

where

DSR is the desertification severity risk to be estimated

N is the number of parameters or components involved in the methodology

i is the severity class index taking values within each class (from 1 to 4 classes) for each parameter, as explained previously

In this presentation, there are four parameters, namely, drought (D), soil erosion (SE), groundwater (GW), and water chemicals (WC), as described earlier.

3.5 Summary and Conclusions

This chapter consists of an analysis of the environmental impacts of drought leading to a quantitative classification of desertification severity. At first, a brief description of drought concepts, types, quantification, indices, features, and assessment is presented. This is followed by a conceptual and comprehensive presentation of desertification, including causes, factors, stages, assessment methods, and mitigation. Then, a two-stage methodology for the quantitative classification of desertification severity is presented, which constitutes the core of this chapter, starting from quantitative drought assessment and resulting in desertification severity classification. Specifically, a combination of the drought severity maps, soil erosion rates, groundwater depth, and, if required, water chemical concentrations is conducted using mapping techniques to produce composite mapping and a spatial model for assessing quantitatively the risk of desertification. Then, classification of the DSR of the study area or watershed is considered and risk classes are defined using standard statistical methods. This classification of desertification severity constitutes a very useful contribution, since it allows a better understanding of desertification factors and causes, leading to potentially effective mitigation measures. Needless to say, with nearly one in six people worldwide presently at risk from the impacts of land degradation, much work remains in terms of monitoring and preventing desertification, understanding causal interactions, and capacity building.

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