10 Badland Systems in the Mediterranean

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10.1 INTRODUCTION

The term *badlands* is currently used for areas of unconsolidated sediments or poorly consolidated bedrock, with little or no vegetation, that are useless for agriculture because of their intensely dissected landscape. Drainage density by V-shaped valleys is usually very high, and some of the degraded landscapes relate to piping erosion, mass movements or the outcrop of shallow saline groundwater (not necessarily characteristic of dissected landscapes) (Bryan and Yair, 1982b). Badlands are different from gullies in the sense that they are not only linear erosive forms normally cut in loose sediments, but also include hillslopes and divides that are usually carved in soft bedrock. Nevertheless, both forms may be closely related, as badland areas may be initiated or reactivated by gully development (Nogueras et al., 2000).

Badlands are frequently considered to be landscapes that are characteristic of dryland areas. Nevertheless, they also occur in wetter areas where high topographic gradients, bedrock weakness and high-intensity rainstorms, which are rather frequent in Mediterranean environments, coexist. This chapter, therefore, seeks to analyse badland dynamics for a range of precipitation which includes subhumid areas, explicitly incorporating the role of vegetation, not discussed in former reviews of badlands (Bryan and Yair, 1982a; Campbell, 1989). Examples are mainly from Spain, where a variety of environmental conditions are found, but also from other Mediterranean areas. The emphasis is mostly on surface processes, whilst the role of tectonics, relief and base level in influencing badland occurrence, although important within a geological context (Harvey, 1987; Alexander et al., 1994), has not been considered in this chapter.

10.2 GEOLOGICAL CONTROLS OF BADLAND OCCURRENCE AND FORMS

The main factor controlling badland formation is the particular character of the rocks or other materials which form the base for the interaction of weathering and erosion processes (Campbell, 1989). However, the existence of highly eroded slopes means the previous or simultaneous development of a high relief where a protective caprock has been removed and/or stream downcutting has occurred (Howard, 1994). In most Mediterranean regions Quaternary tectonics have been quite active, resulting in past and/or present uplifting in most badland

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areas. Badlands form on soft or unconsolidated geological materials, mostly *soils*, or some *sediments or sedimentary rocks* (aeolian, glacial, colluvial and alluvial deposits).

Soils in badlands deserve special attention, because soils are the inter-phase between the lithosphere and the atmosphere, and so constitute one of the key elements either favouring or restricting the initiation of badland formation. When soils are resilient against erosion processes, gullies do not form; however, when soils, either because of their particular ground cover, i.e. sparse vegetation, and/or intrinsic properties, cannot withstand erosive forces, the topsoil is eroded and deep gullies develop, which may give rise to badlands if the underlying material is also erosion-sensitive.

Consequently, the characteristics of the materials underlying soils are crucial for the development of true badlands. However, not only does the degree of consolidation define a badland-prone material, but cementing agents and particle size range and distribution are also crucial.

Lithology is a major factor for badland production, and is probably of greater importance than tectonics, climate, topography or land use (Campbell, 1989; Gerits et al., 1987; Imeson and Verstraeten, 1988; Calvo et al., 1991a,1991b). The general characteristics of a soil, regolith or geological formation that favours badland relief are the unconsolidated or very poorly cemented material of clay and silt, sometimes with soluble minerals such as gypsum or halite (Scheidegger et al., 1968). Specific characteristics, like structure, mineralogy, physical and chemical properties, may play either a primary or secondary role in material disintegration and badland development. Fourteen badland areas, mainly from the western Mediterranean, are examined as examples (Table 10.1).

10.2.1 Structure–Microstructure; Morphology–Micromorphology

Both shales and mudstones have a considerable network of fissures and cracks, mainly due to unloading stresses when the bedrock goes from deep burial to near Earth–surface conditions, either because of tectonic activity or erosion dismantling the Earth's upper crust. This network of cracks and fissures, which can be seen through an optical microscope (Figure 10.1), is the predominant entry for atmospheric fluids coming into close contact with the rock and starting weathering processes. In Tabernas gypsiferous mudstones, gypsum-filled cracks are responsible for mudstone breakdown once the gypsum dissolves (Cantón et al., 2001). In Vallcebre mudstones, smectite aggregates start to swell when a network of cracks and fissures connects with atmospheric solutions (Solé et al., 1992).

Individual particles and/or clay aggregates, when observed through the scanning electron microscope (SEM), are seen to have important intergrain pore spaces (Figure 10.2), which may conduct weathering fluids by capillarity.

From fresh mudrock to the weathered state, shales and mudrocks have been monitored for temporal changes in their surface morphology by means of sequential photography (Farres, 1978; Harvey, 1982, 1987; Regüés et al., 1993, 1995; Pardini et al., 1995; Cantón et al., 2001) or from the differences between wet and dry bulk densities (Imeson, 1986; Bouma and Imeson, 2000). In all cases, changes were very fast and usually related to porosity enhancement.

10.2.2 Mineralogy

Certain minerals play an essential role in the breakdown of some rocks at near surface conditions and can be divided into two great groups: (a) those which may become soluble, like all soluble salts (halite), but also moderately soluble like sulphates (gypsum) or carbonates (calcite

Table 10.1 Characteristics of badland areas (mainly from the western Mediterranean)

Reference	Location	Rock age	Type of rock	Sand	Silt	Clay	Gypsum	$CaCO_3$ eq.	Smectite	SARp	WCT
Cantón, 1999	Tabernas (SE Spain)	Upper Miocene	Calcaric-gypsiferous mudstone	10	80	10	10–30	30	(+)	1–25	2
Berrad et al., 1994	Albox (SE Spain)	Upper Miocene	Calcaric-gypsiferous claystone	0	50	50	3–15	30	++	1–16	1
Gerits et al., 1987	Guadix (SE Spain)	Eocene–Miocene	Marine marl	9	62	29	3	50–60	n.a.	20–80	n.a.
Unpublished data	Los Guillermos (SE Spain)	Neogene	Claystone	15	75	10	0–4	40	+ + +	1–7	1
Martín-Penela, 1994	Vera (SE Spain)	Upper Miocene	Gypsiferous mudstone	n.a.	>50	>40	+ + +	Marls	(+ + +)	n.a.	n.a.
Unpublished data	Abanilla (SE Spain)	Neogene	Mudstone	9	76	15	7–12	22	(+)	1–40	2
Harvey and Calvo, 1989	Petrer (SE Spain)	Cretaceous	Marl	13	68	19	Traces	60	++	1–50	1
Benito et al., 1992	Huesca (NE Spain)	Miocene	Shale	n.a.	n.a.	n.a.	0	+	(+)	13–42	n.a.
Solé et al., 1992	Vallcebre (NE Spain)	Late Cretaceous	Mudstone	10	55	35	0	30–50	+ + +	<1	1
Meunier et al., 1987	Draix (SE France)	Middle Jurassic	Black marls	n.a.	n.a.	n.a.	0	30–60	(+)	n.a.	n.a.
Torri et al., 1994	Volterra (Central Italy)	Pliocene	Silty clay sediments	2	50	48	0	16	(+)	21	n.a.
Yair et al., 1980	Negev (S. Israel)	Cretaceous–Neogene	Sediments	n.a.	n.a.	30–80	+	+	+ + +	n.a.	n.a.
Gomer.D., 1995	Oued Mina (N. Algeria)	Triassic–Jurassic	Marls	Silty to silty clay			n.a.	+	n.a.	n.a.	n.a.
Imeson et al., 1982	Beni Boufrah (N. Morocco)	n.a.	Silty colluvial sediments	4–80	11–46	8–54	0	1–34	–	20–34	n.a.

n.a. = not available. SARp = practical Sodium Absorption Ratio. WCT = Water Coherence Test.

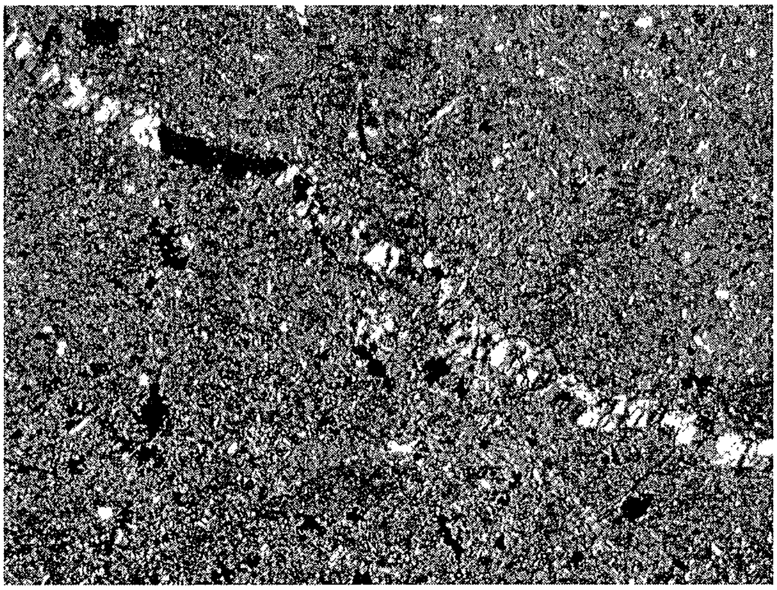

Figure 10.1 Photomicrograph (under cross-polarised light) of a fresh gypsiferous mudstone showing a crack filled with gypsum (from upper left to bottom right)

Figure 10.2 SEM image of a calcium–gypsiferous mudstone from Tabernas, showing a phantom of a typical twin gypsum crystal

and dolomite), especially when they can be dissolved because of the small size of their constitutive particles and/or solvent characteristics (Cantón et al., 2001); and (b) those swelling upon wetting, like clays, some of which, like smectite, can absorb water in amounts several times their dry weight, with consequent volume increases. Almost all lithologies in Table 10.1 reveal the presence of smectite.

10.2.3 Texture

Badlands usually develop on fine-grained clayey or silty sediments which come under the general generic heading of 'shale' (consisting of bedded silts, clay mud, siltstone, mudstone, mudshale, clayshale, claystone) (Fairbridge, 1968). Those developed around the Mediterranean are not an exception. Most parent materials are essentially silt-dominant, with clay as the second particle size, while sand is in general very poorly represented (Table 10.1).

Texture depends on four factors: particle-size distribution, grain shape, degree of crystallinity and relationship among grains (Terzaghi and Peck, 1967). Of these, particle-size distribution plays the key role in susceptibility for material disintegration and erosion: the larger the range of particle sizes, the higher the degree of packing, and hence the greater resistance to breakdown processes. This is especially true of materials that underwent minimum burial (Taylor and Smith, 1986). Conversely, the narrower the particle-size distribution, the higher the susceptibility for material disintegration, piping and, consequently, for badland development (Terzaghi and Peck, 1967). Particle-size analyses, by means of laser diffraction (Cantón, 1999; Pardini, 1996) from several badland sites around the Mediterranean (Table 10.1) show quite uniform fine textures: D_{60} ranges from 2.3 to 24 μm and D_{10} ranges from 1 to 3.7 μm. Uniformity coefficients (D_{60}/D_{10}) range from 2.3 to 9 μm, with a median of 3.5 μm, and indicate quite a uniform particle size.

10.2.4 Physical Properties

Besides textural properties, porosity is the second most important physical property. While being a considerably compacted rock in the fresh state, the overall porosity of mudstones determined by Hg-intrusion porosimetry is relatively high, around 10%, and steadily increases upon weathering up to the range of upper soil values, commonly 40–60% (Figure 10.3) (Solé et al., 1992; Bouma and Imeson, 2000; Cantón et al., 2001). The initial porosity of the fresh mudstone seems to enhance or restrict further weathering, leading to badland formation; in addition, the higher the macroporosity, the more unstable the badland regolith type (Imeson, 1986; Solé et al., 1992).

Geomechanical properties provide another important control for erosion: Atterberg limits (for consistency), swelling, and slaking behaviour are considered in many badland studies.

Consistency limits (Atterberg plastic and liquid limits) are good indices of material reactivity in relation to water; the higher the difference between them (known as the plasticity index I_p), the more stable the material. Shales, mudrocks and their weathering products usually have very low I_p, in a range from 4 to 20. Those from Spain in Table 10.1 have a median around 14, indicating their high susceptibility to fluidification.

Material coherence – or its opposite, slaking behaviour – can be evaluated by means of either the water coherence test (WCT; Emerson, 1967) or a modified version (Gerits et al., 1987). On a scale from 1 to 7 (least to most coherent) most badland-prone shales and mudrocks score 1 or 2, which is high slaking behaviour (Table 10.1).

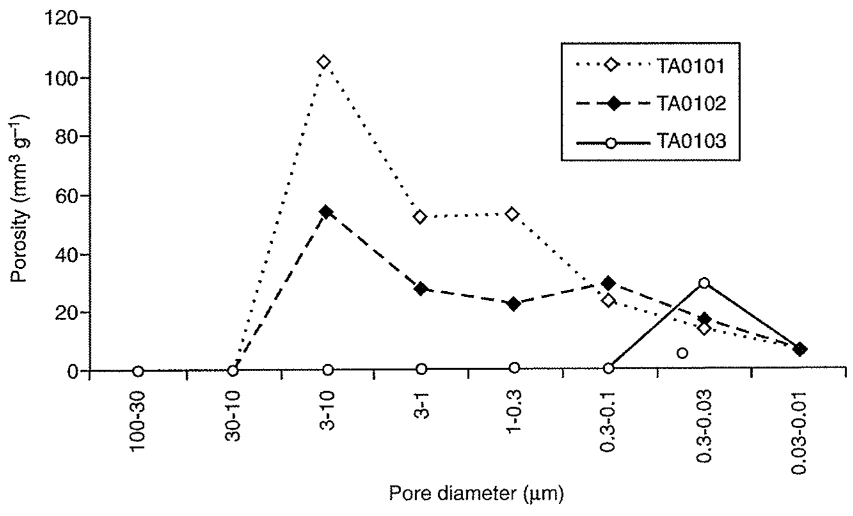

Figure 10.3 Hg-intrusion porosimetry of samples from a weathering profile. Identification and total porosity ($mm^3\,g^{-1}$): TA0103 = third deepest layer, fresh mudstone (33.72); TA0102 = second layer (131.15), TA0101 = upmost, surface layer (250.25)

Swelling indices, while common in geotechnical studies, have been little used in badland studies. The Lambe (1951) swelling test was used by Berrad et al. (1994) to characterise erosion behaviour of soils in southeast Spain. The COLE index was also used: this evaluated three-dimensional and linear expansion of soft materials, like soils developed from marls at two sites near Guadix (southeast Spain) and in northeast Morocco (Gerits et al., 1987; Imeson et al., 1982).

10.2.5 Chemical Properties

The cohesion of mudrock is commonly due to thin films of slightly soluble cementing material. When mudrocks are permanently located above the water table, which is the case in most semi-arid Mediterranean regions, they are quite stable. However, submerged mudrocks, even for short periods, are likely to be very unstable because of their relatively high porosity and because of the leaching effects of submergence. Leaching removes the cementing substances and transforms the weathered mudstone into an almost cohesionless material that is no longer stable (Scheidig, 1934). In semi-arid regions, the stability of mudrocks is illusory because there are very short periods of local wetting followed by complete drying-out periods which destabilise the mudstone either through wetting–drying or solution–crystallisation processes (Goudie, 1990; Cantón et al., 2001).

Clay dispersion is a physico-chemical process relevant to erosion processes, particularly to the development of pipes, as discussed below. Materials (soils, regoliths or rocks) with a potential to disperse are those which contain a high exchangeable sodium percentage (ESP), saturating part of the exchangeable cations of their clays. This percentage is considered to be critical when higher than 13. As this parameter is relatively complicated to obtain, a wellcorrelated value has been designed by soil salinity specialists (USSLS, 1954), known as the sodium absorption ratio (SAR), which is easily calculated from the soluble cations extracted from the soil (rock or other material) saturated paste according to:

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2}}$$

where Na^+, Ca^{2+} and Mg^{2+} represent the concentrations of these cations in milli-equivalents per litre (meq l^{-1}). Lithologies, regoliths and soils with ESP or SAR values higher than 13 (SSSA, 1997) are susceptible to chemical dispersion upon wetting, meaning that they are destructured materials which cannot withstand the erosive impact of water.

10.3 GEOMORPHIC PROCESSES

10.3.1 Weathering

As most badlands are developed on bedrock, some weathering process is needed before erosion processes can act. Indeed, badlands are usually carpeted with the product of weathering called *regolith*, defined as the entire mantling cover of unconsolidated material on the surface of the Earth's crust regardless of its origin, though mostly formed by weathering of unaltered rocks (Fairbridge, 1968). Regolith is very vulnerable to erosion because it is usually composed of unbound mineral particles.

Regoliths may be considered as a special kind of soil, characterised mainly by very low organic matter content and mineralogical and chemical characteristics close to those of the parent rock, although with higher porosity because of physical weathering processes. Nevertheless, where parent rocks bear significant contents of gypsum or soluble salts, regoliths may become impoverished in these soluble materials because of leaching processes working alongside the physical weathering (Cantón et al., 2001). In badland areas with moderate erosion rates, the evolution of regolith may be complex, through the formation of shallow horizons with more compact structure and lower porosity, usually named *crusts*, that may be purely physical or may incorporate algae or lichens (Alexander and Calvo, 1990; Solé et al., 1997).

The literature on Mediterranean badlands indicates that a few weathering processes seem to contribute to their formation: wetting–drying (including swelling–shrinking, slaking and salt solubilisation–crystallisation) and freezing–thawing.

The action of wetting–drying cycles is the weathering process most commonly claimed for regolith formation. Indeed, water content variations mean changes in capillary forces able to perform significant physical work (Regüés et al., 2000), leading to the progressive disintegration of soft rock as observed in experimental conditions (Pardini et al., 1996; Cantón et al., 2001). Only a few wetting–drying cycles contribute to enlarge total porosity (Figure 10.4), which is assessed by the significant increase in the water absorption capacity of the mudstone (Cantón et al., 2001). Actually, in Tabernas badlands, a combination of three factors is responsible for mudstone weathering: repeated cycles of wetting–drying, existence of some primary porosity (intergrain pores and cracks and/or fissures from both uplifting and tectonic activity), and solubilisation–crystallisation of relatively soluble minerals, with gypsum the most abundant within this category. Also, a few wetting–drying cycles have been sufficient to reveal ion migration (especially Na^+, Ca^{2+}, Mg^{2+}, SO_4^-, HCO^- and Cl^-) within the mudstone, which leads to mineral dissolution (Cantón, 1999; Cantón et al., 2001).

Swelling–shrinking processes imply the presence of swelling clays, like smectite. In addition to mineralogical characterisation, the magnitude of this process can be assessed by the Lambe

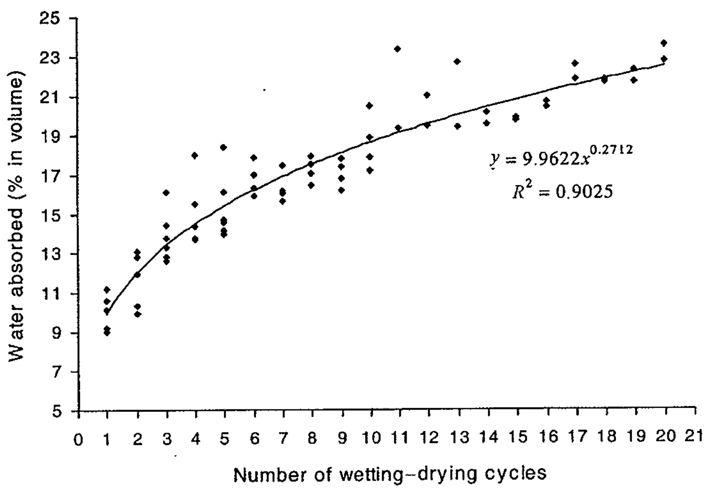

Figure 10.4 Water absorbed in a series of replicated mudstone blocks during 20 wetting–drying cycles and best-fitting model

swelling test or by the COLE index, as discussed above. Wetting–drying alternations in materials with expansive clays (smectite) cause the formation of nets of deep cracks and may also lead to the formation of a shallow layer of loose expanded regolith fragments, usually called *popcorn* (Hodges and Bryan, 1982).

Rapid wetting of air-dry fine materials can lead to aggregates bursting because of the compression of air trapped between the wetting fronts driven by capillary forces – a process called *slaking* (Yoder, 1936) that is relevant to erosion (Imeson and Verstraeten, 1989; Solé et al., 1992). Physico-chemical slaking has been found to be the main detachment mechanism in highly dispersive sodium-rich clays (Gerits et al., 1987) to the point that the detachment rate is controlled by the rate of advancement of the wetting front (Torri et al., 1994).

In areas subjected to freezing cycles, as in the Pyrenees and the Marnes Noires area in France, the weathering role of gelivation may be much more important than wetting–drying (Clotet et al., 1988, Regüés et al., 1995, Oostwoud Wijdenes and Ergenzinger, 1998). The growth of ice crystals on the freezing front, along with the cryosuction of the water retained in the matrix, can cause the breakdown of the rock and lead to the formation of a layer of popcorn without the existence of actual wetting–drying cycles, as observed in laboratory experiments (Pardini et al., 1996). In these environments, harsh thermal conditions and high regolith instability in shady aspects may provide a more important check on vegetation spreading than dryness on sunny aspects, leading to the increased occurrence of badland surfaces on these wetter aspects (Regüés et al., 2000).

10.3.2 Soil Formation and Resilience in Badland Environments

In badland areas, more- or less-developed soils do not form a continuous three-dimensional body covering the entire landscape. On the contrary, soils are restricted to those landscape patches where geomorphic agents allowed their accumulation or have not been able to destroy them. Usually badlands consist of mosaics of physiographic units where all the stages can be found between the bare parent material at the bottom and/or sides of gullies, and soils with some kind of vegetation cover in more stable positions. These mosaics are especially complex in semi-arid Mediterranean landscapes. In Tabernas, southeast Spain, strong interrelationships have been found between soil development, ground cover type, hydrological and geomorphological behaviour, and topographical attributes (Alexander et al., 1994; Cantón, 1999).

In a badland area it is important to distinguish between a developed soil and a regolith, which is the initial stage of soil formation. Steep slopes and gullies do not allow the formation of a developed soil because erosion processes are either frequent and/or intense. Soils are usually found on relatively stable surfaces because they result from either the evolution of the in-situ parent material or any accumulation of sediments, as in pediments or fluvial terraces.

Despite the similarity in parent material characteristics in a given badland area, differences exist in the relative importance of the soil properties, due in part to environmental or historical factors (Imeson et al., 1982; Solé et al., 1992; Torri et al., 1994). Almost all five recognised factors of pedogenesis (parent material, climate, topography, living beings, and time) differ within short distances in badland environments, depending on which physiographic unit is examined. Developed soils are found on flat or moderate slopes where climate and topography have acted together for enough time to leach weathering agents or to change particle-size distribution from the parent material. The development of some horizons may even decrease soil erodibility, while colonising plants provide protective ground cover and increase organic matter content and, thus, aggregate stability. Bare regoliths are mostly found on steep slopes where runoff and erosion predominate; colonising plants cannot provide enough cover or are not able to change regolith properties for a steady soil development. Intermediate states are found on moderately steep slopes where incipient soil development is favoured by a continuous or discontinuous cover of colonising species such as lichens, mosses or microphytic crusts. However, not all pedogenic processes lead to more resilient soils. In some instances, leached salts from upper parts of the landscape can accumulate downslope and produce either gypsic, saline or sodic horizons that restrict vegetation growth and/or decrease the soil resistance to erosive agents.

In general, the greater the soil resistance to erosion, the better protected will be the badland-prone material underneath. Soil resistance is related to both soil cover and intrinsic soil characteristics, like aggregate stability, which is strongly dependent on the amount and type of organic matter and clay. Organic matter content is related to both climate and vegetation. However, erosion is influenced not only by soil erodibility, but also by the impact of climatic erosivity, which can in some circumstances overcome the intrinsic resistance of a soil.

10.3.3 Infiltration and Runoff

Soil surface characteristics control infiltration, soil moisture and temperature regimes, runoff, and hence soil and landscape evolution. For this reason, soil surfaces are important in the understanding of badland evolution and geomorphological behaviour. Weather simulation has been used by several authors to study the response of badland surfaces to rainfall (Scoging, 1982; Imeson and Verstraeten, 1988; Calvo et al., 1991b; Solé-Benet et al., 1997; Bouma and Imeson, 2000; among others). On most badland surfaces water infiltrates with difficulty due to the presence of surface crusts or seals. Actually, all authors agree on the complexity of the response because of the high spatial and temporal variability of regolith properties. Runoff response is usually fast, with a very short 'time to runoff', less than 4 minutes in a variety of experiments (Imeson et al., 1982; Calvo et al., 1991b; Solé-Benet et al., 1997) and infiltration fronts reduce to a few centimetres. Micro-relief patterns due to micro-rills, crustose lichens, pedestals or pinnacles cause particular infiltration and runoff responses because the flow follows the micro-channels left by the micro-relief (Imeson and Verstraeten, 1988; Solé et al., 1997).

Nevertheless, badland regoliths may allow high infiltration rates when there are open cracks or highly porous popcorn structures. On badland surfaces with deep cracks, true overland flow may be rare, and crack flow can feed rills and main channels with water and sediment during storms that are not of sufficient duration to lead to crack closure (Yair and Lavee, 1985). In areas with shallower cracks or with longer rainfall events, crack closure usually means a strong reduction in permeability, allowing overland flow to occur. Therefore, the formation of runoff during storms may be a complex phenomenon that depends on lithology, antecedent conditions or a sufficient duration of the storm (Hodges and Bryan, 1982; Regüés et al., 1995). In areas subjected to freezing during winter, infiltration rates may show a clear seasonal pattern, being high in winter because of the formation of a deep highly porous regolith, and lower at the end of the non-freezing season because of regolith compaction and depletion (Regüés et al., 1995).

10.3.4 Erosion Processes

Rainsplash

During rainstorms, the impact of raindrops contributes to the destruction of popcorn layers and to the sealing of cracks, through the clogging role of detached regolith particles. In badlands with highly dispersive clays, the fine, detached particles may flow through cracks and micro-pipes from the beginning of the storm (Torri et al., 1994; Torri and Bryan, 1997), whereas in less dispersive materials, detached particles are transported by overland flow after the permeability and roughness of the regolith surface have been attenuated. Rainsplash is usually a very active process of detachment, as demonstrated through rainfall experiments and by the frequent existence of regolith pedestals below rock fragments and small plants (Regüés et al., 1995).

Piping

In badland areas developed on clay materials which are highly expansive or with high exchangeable sodium content, flow and particle detachment on a crack network can evolve into the extensive development of a net of pipes (Hodges and Bryan, 1982; Alexander, 1982; Torri et al., 1994), although dispersivity seems to be more relevant than expansivity (Gutiérrez et al., 1988). Piping phenomena may also cause the expansion of channel headcuts or gully margins by the collapse of macro-pipes or tunnel expansion (Harvey, 1982; Gutiérrez et al., 1988, López-Bermúdez and Romero-Díaz, 1989), which may also be developed in sediment fills of older dissected forms (Gallart, 1992).

Rills

These are very common micro-forms on badland surfaces, although they are usually non-permanent because of the diffusive role of drying or frost weathering. Nevertheless, rills usually reappear during rainfall events and are significant in sediment production and water and sediment conveyance. In badlands with thick cracked regoliths, rills may be fed by water and sediment, not through overland flow but through crack and micro-pipe flow (Bryan et al., 1978; Gerits et al., 1987). In badland surfaces with expansive materials where rills are fed only by crack and micro-pipe flow, it has been suggested that rills may not be formed by the classical role of overland flow, but by the collapse of areas close to the base of the regolith where moisture due to the formation of a perched water table reaches a critical value for liquefaction (Imeson and Verstraeten, 1988). This hypothesis may explain why rills on steep badland surfaces are frequently parallel (with few junctions) and start from the top of the divides without a band that is free of erosion. Following this hypothesis, space between rills would decrease as the slope increases, which reduces the threshold of moisture content for collapse, and would increase with the development of the crack system, since the higher efficiency of the subsurface drainage of the regolith would prevent local saturation.

Shallow Mass Movements

Regoliths in steep badland hillslopes are frequently affected by shallow mass movements during rainfall events or rainfall experiments. The unstabilised regolith mass may flow towards the valley bottom in the form of small mud or debris flows (Hodges and Bryan, 1982; Oostwoud Wijdenes and Ergenzinger, 1998). Poorly cracked regoliths are more prone to shallow mass movements due to easier saturation (Gerits et al., 1986) and pieces of coarser regolith may collapse or suffer some transfer downslope without reaching the channel system. Steep hillslopes can also be subject to the fall of regolith fragments, especially during dry periods (Gallart, 1992). In mountain areas with badlands developed on relatively cohesive marls, mass movements in the form of debris falls may be the main transport process of sediments from hillslopes to the channel network. Because of the coarseness of the materials eroded from hillslopes, the contribution of bedload transport to the total sediment exported from these areas ranges between 40 and 80%, decreasing with the increasing size of the catchment because of the increased attrition with increasing catchment size (Richard and Mathys, 1999). Frost creep may also be an active process of sediment transport along badland hillslopes in mountain areas, moving individual particles or pieces of frozen regolith.

Deeper Mass Movements

These are sometimes related to badland initiation and evolution, but their activity disorganises the characteristic fluvial landscape. Slumps or rapid wasting of soils may lead to the outcrop of bare soft rock triggering the formation of badlands (Clotet et al., 1988). On the other hand, the dissection of badlands may increase the topographic gradients and lead to the destabilisation of hillslopes (Alexander, 1982).

10.3.5 Erosion Rates

Badland areas look as if they have been caused by very rapid erosion. Erosion rates in badlands have been measured by three main methods, classified according to the temporal scale: (1) *long-term* methods (10^3–10^5 years) consist of the estimation of incision depths below some landscape element of known age (Yair et al., 1982; Bryan and Yair, 1982b); (2) *short-term* methods (1–10 years) usually form part of monitoring programmes and include the measurement of ground lowering using erosion pins (Alexander, 1982; Campbell, 1982; Benito et al., 1992; Clotet and Gallart, 1986; Lecompte et al., 1996), frames or profiles for detailed micro-topographic description of plots or sections (Campbell, 1974; Benito et al., 1992) and repeated topographic surveying (Schumm, 1956; Egels et al., 1989), as well as the monitoring of sediment production from small areas (Clotet and Gallart, 1986; Gutiérrez et al., 1995; Castelltort, 1995; Sirvent et al., 1996 and 1997) or small catchments (Richard and Mathys, 1999); and (3) *medium-term* methods (10–10^2 years) consist of the measurement of the volume of sediments retained by some trap that acted during a period of time that was too long to monitor (Clotet et al., 1988).

Nevertheless, erosion rates that are estimated through the different methods may show inconsistencies. For example, local short-term methods usually give higher rates than whole-landscape long-term methods (Yair et al., 1982), but this can be explained by the fact that erosion rates in a badland system vary from one point to another – an element that is very active at one moment may be fairly inactive a few decades later. Local topographic measurements (erosion pins) must be treated with special caution as they rarely cover entire functional units and can be prone to error as a result of ground expansion during the weathering processes. Short-term measurements through erosion pins may lead to completely inconsistent rates (or even negative ones) because periods of major regolith depletion alternate with periods of regolith formation, through bedrock expansion.

An example of the comparison between different methods is shown in Figure 10.5, which represents erosion rates in the badlands of the Vallcebre area (eastern Pyrenees, Spain) that were estimated through monitoring by erosion pins and two small plots (4 and 37.5 m^2 respectively), and the measurement of the volume of sediments in a 40-year-old natural trap that dammed a catchment of 3.1 ha (Clotet et al., 1988). Micro-catchment rates were obtained through the monitoring of sediments from an elementary catchment of 0.17 ha (Castelltort, 1995). The high temporal variation in rates obtained through erosion pins is caused by the expansion of regolith during freezing periods in winter. The uncertainty of badland erosion

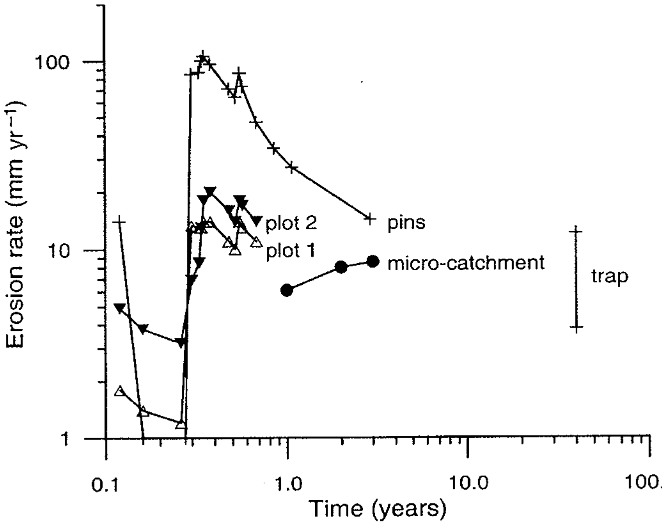

Figure 10.5 Erosion rates obtained through different methods and different time spans in badlands at Vallcebre (eastern Pyrenees, Catalonia, Spain). Original data from Clotet et al. (1988) and Castelltort (1995)

rates measured in the natural trap is due to the fact that badlands cover only 12% of the contributing catchment, and semi-degraded areas with visible erosion features cover 26%. Sirvent et al. (1997) compared erosion rates obtained through erosion pins, profilometers and sediment collection during a one-year period in an area free from freezing, and found differences of up to 20–30%, similar to differences with the same method at various points of the same badland unit.

The rates of badland erosion in dry areas are much more moderate than the appearance of the landscape leads one to expect (Yair et al., 1982; Wise et al., 1982). This paradox is only apparent because it is known that dry areas have limited potential for erosion (Langbein and Schumm, 1958), yet also have little potential of landscape recovery after infrequent geomorphic events (Wolman and Gerson, 1978). Badland areas are not protected by vegetation, and under the general scheme proposed by Langbein and Schumm (1958), erosion rates should be expected to grow rapidly with increased precipitation.

Erosion rates estimated for badland areas with different annual rainfall totals show indeed an increasing trend (Figure 10.6). Point Z represents long-term erosion rates estimated for the Zin-Havarim badlands in Israel using topographic lowering (Yair et al., 1982). Light point C represents a one-year erosion rate measured through monitoring of an elementary badland unit, whereas bold **C** represents the estimate of long-term channel incision assessed by the weathering rate, both at El Cautivo, Tabernas, southeast Spain (Cantón, 1999). Point A represents the long-term erosion rate in the Alberta badlands in Canada, estimated with the same method as for point Z (Bryan and Yair, 1982b). Point B represents a one-year erosion rate obtained through sediment monitoring from an elementary badland unit at Las Bardenas, Ebro depression, Spain (Gutiérrez et al., 1995). Light points V were obtained through the same method in the Vallcebre area, and bold **V** represents the three-year average (Castelltort, 1995). Finally, bold points **L**, **M** and **R**

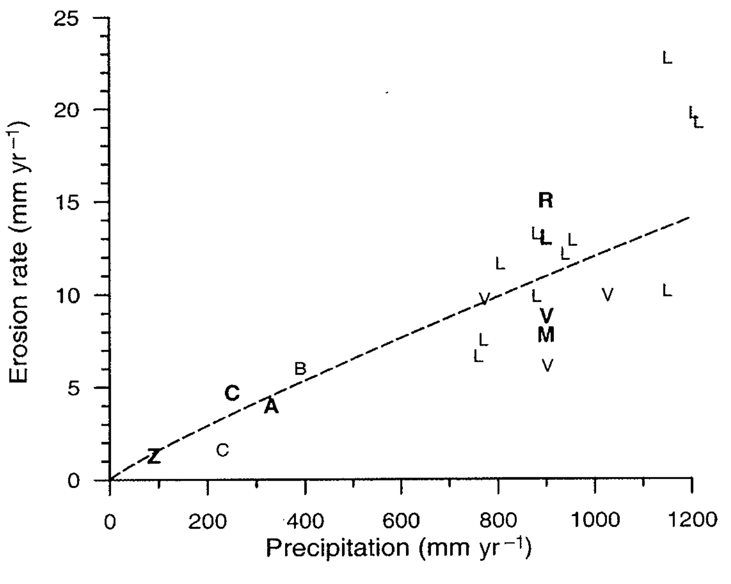

Figure 10.6 Erosion rates in badland areas across a wide range of precipitation. See text for explanation of the symbols and references

represent 11-year averages obtained through monitoring sediment discharge from small catchments of 0.13 ha (**R**), 8 ha (**M**) and 86 ha (**L**) in the experimental area at Draix, southeast France (Richard and Mathys, 1999), whereas light L points represent annual rates. Nevertheless, this graph does not necessarily mean that erosion rates in a badland area increase if the yearly precipitation increases in a geographic location; this may happen for annual values, but increased precipitation can also lead to the stabilisation of badlands because of increased vegetation cover (Nogueras et al., 2000). The relationships between vegetation, erosion rates and rainfall amounts are somewhat intricate, as will be discussed below.

On the other hand, in most kinds of soft bedrock where badlands are developed, erosion rates may become limited by weathering rates, both of which are controlled by lithology (Lecompte et al., 1996). This has been suggested in semi-arid areas where fresh bedrock outcrops in channel beds (Cantón, 1999) as well as in semi-humid areas where regolith is depleted almost every year (Clotet et al., 1988; Regüés et al., 1995). Nevertheless, some adjustment between erosion rates and weathering may be suggested, as regolith protects bedrock from weathering (Regüés et al., 1995, 2000), erosion rates in badlands usually being considered transport-limited (Campbell, 1989).

Finally, it is worth emphasising that the sediments coming from badland areas may be deposited on alluvial fans or plains after short transport. The drier the climate, the more ephemeral and local are runoff events, providing few chances for distant transport. In more humid climates, intense showers during summer are the main erosive circumstance, whereas long-distance transport is effected by long-lasting runoff events fed by autumn or winter rains of moderate intensity (Gallart et al., 1998).

10.4 VEGETATION AND GEOMORPHIC EVOLUTION OF BADLANDS

Both high erosion rates and low vegetation cover are related by feedback relationships that are at work in badland areas. Low vegetation cover means that the ground surface is unprotected against rainsplash and overland flow, whereas high erosion rates impoverish the soil's capacity to bear vegetation and make seedling survival difficult because of the physical instability of the ground (Guàrdia and Ninot, 1996; Guàrdia et al., 2000).

The implications of these features on the evolution of badlands are approached in two complementary ways in this section. The first is a computer experiment that tries to explore the occurrence of badlands along a precipitation range; as such, it works on a broad scale, bulking all the spatial differentiation of processes and rates, and does not attempt to explain their evolution through time. The second approach reviews the characteristics and role of the vegetation that grows in badlands on a narrow scale with emphasis on the issue of spatial patterns. Finally, a discussion integrates the outcomes of the two approaches.

10.4.1 Relationships between Erosion Rates and Vegetation through a Precipitation Range

In arid areas, both the potential for vegetation colonisation and the erosion rates are low; vegetation therefore plays a negligible role and badland dynamics are slow (Yair et al., 1982) and fully controlled by physical processes (Yair and Lavee, 1985). Nevertheless, badlands also occur in more humid areas where vegetation can control erosion rates; in these areas badland landscapes are poorly vegetated areas where high erosion rates and impoverished vegetation cover are related by feedback loops.

A simplified computer simulation model has been developed for analysing the interaction between vegetation and geomorphic processes for a wide range of annual precipitation. The model is built up with one independent variable (annual rainfall), two state variables (vegetation cover, regolith thickness) and two geomorphic processes (weathering, erosion). Weathering and erosion rates have been adjusted for soft rocks, characteristic of badlands. The annual rainfall positively controls vegetation cover, weathering rate and erosion rate. Weathering increases regolith thickness, which favours vegetation cover but decreases weathering rate itself. Erosion rate is diminished by vegetation cover and restricts vegetation cover itself and depletes regolith thickness. Vegetation growth rates are not directly simulated but the effect of erosion on vegetation increases for decreasing rainfall. A relevant limitation of this model is that it does not take into account the feedback role of increasing local topographic gradients when a badland area has already developed.

Mathematical expressions for the former relationships were established from previous studies when possible (Kirkby, 1976; Ahnert, 1987; Stocking, 1988) or postulated from field observations; they are all continuous functions. This approach represents a crude simplification of the system. The aim is to provide a tool for fundamental discussion but not for application, and attention is therefore paid to the qualitative description of the behaviour of the system rather than to exact rainfall depth, erosion rate or vegetation cover values.

Different values within the full range of state variables (vegetation cover, regolith thickness) for every constant annual rainfall amount within the gradient (from 50 to 1000 mm) were used as starting conditions for the model, which was run by iterations and stopped when relative rates of change were smaller than one per thousand in both state variables (stability condition). The degree of stability of the system at every value of vegetation cover was then obtained by averaging the inverses of rates of change of the system variables for this vegetation cover. (System stability is the degree of permanence of a given condition in a dynamic equilibrium, independent of its geomorphic activity or its state of degradation.) Consistent results were obtained from the beginning, but a few trials with slight changes in equations or parameters were necessary to avoid some spurious irregularities.

Erosion rates at system stability obtained for the different rainfall values are plotted in Figure 10.7. The lower line (dots) represents conditions near the vegetation optimum and shows the same trend as results previously obtained from actual data (Langbein and Schumm, 1958) and through simulation (Kirkby, 1976): erosion rates increase with the increasing rainfall amounts for dry climates, but decline when vegetation cover is sufficiently developed to control erosion. The upper line (triangles) represents another dynamic equilibrium condition at maximum geomorphic activity and gives the first original result: it is very close to the former line for dry climates, but shows a rapid increase for annual rainfall amounts higher than 250 mm because of the increase of available energy without the vegetation control, and finally becomes limited by the weathering rate when it exceeds 500 mm.

System stability estimates for different annual rainfall and vegetation cover values are represented in Figure 10.8. The first remarkable fact shown in this figure is that the model predicts the lack of areas devoid of vegetation for annual rainfall of less than 300 mm; this fact is congruent with the field evidence that badlands in dry areas usually have higher vegetation cover than badlands in more humid areas, sometimes in the form of seasonal vegetation or lichens (Alexander and Calvo, 1990; Solé et al., 1997).

For rainfall values below 350 mm, the model shows a large plateau or a very flat stability field, suggesting that, as in these dry conditions the gradients for system change are low, local degradations may remain for a long time as the natural tendency for recovery is also low.

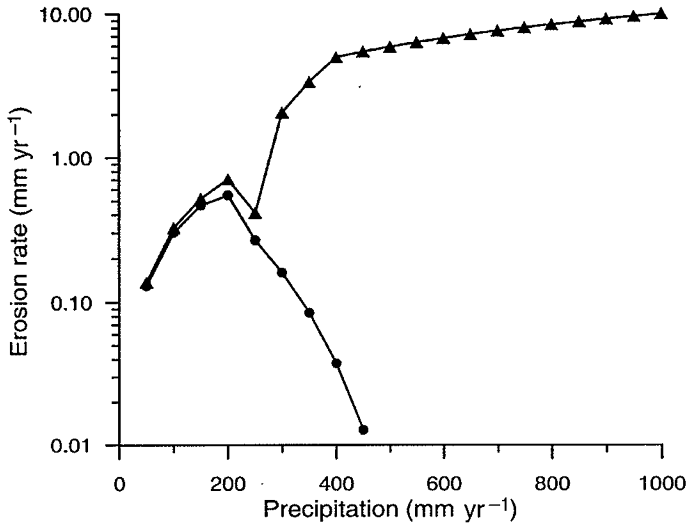

Figure 10.7 Erosion rates reached at system stability for different annual rainfall depths, obtained through a simulation model that analyses relationships between precipitation, weathering, erosion and vegetation cover. The lower line (dots) represents the more vegetated conditions whereas the upper line (triangles) represents the poorer vegetation cover

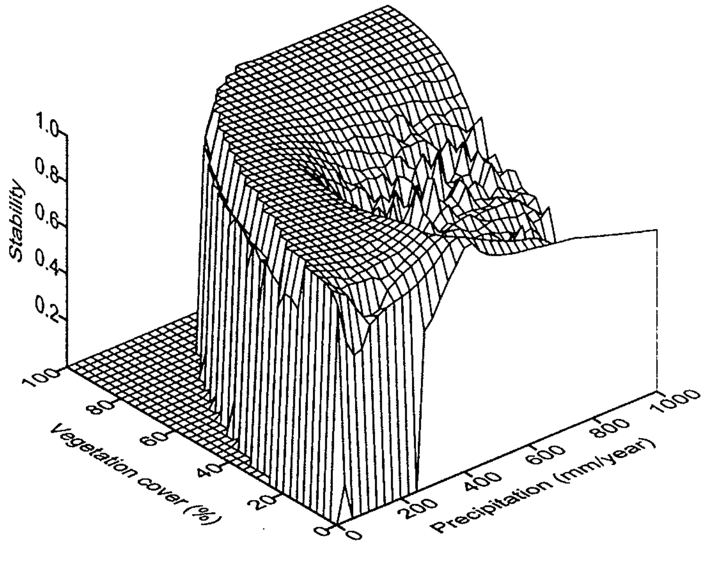

Figure 10.8 System stability estimates obtained with the same model as the former figure, plotted for the respective annual rainfall depths and vegetation cover percentages

Nevertheless, the lack of a distinct high-stability area for badlands in this low precipitation range is due to the fact that badland development is poorly related to vegetation controls and cannot be adequately handled by this approach. As discussed before, this approach does not consider the feedback mechanism created by badland topography.

Between 300 and 500 mm, a relative peak of system stability, situated near 10–20% of vegetation cover, suggests a significant presence of badland areas in those semi-arid climates. As shown in Figure 10.7, the development of vegetation may be sufficient in this precipitation range to control erosion rates, but moderate erosion rates are enough to maintain low vegetation covers, which conversely are not very effective in preventing erosion, thus suggesting that the areas within this range of precipitation may be highly sensitive to badland development because of vegetation disturbances.

Finally, for annual rainfalls higher than 500 mm, the model predicts a clear dichotomy between fully vegetated and completely bare conditions, but the general tendency is towards full vegetation. The range of system stability for bare areas is very narrow, and is maintained by high erosion rates. This suggests that they are triggered by special conditions (human disturbance, mass movements), and have a natural tendency towards recovery, which gives some hope for revegetation work (see also Alexander et al., 1994).

10.4.2 Characteristics of the Vegetation Growing in Badlands

Geomorphic processes responsible for badland evolution operate at different rates over a single landform, and, in consequence, badlands show a high degree of spatial heterogeneity. This feature has implications for the spatial distribution of vegetation, its establishment, and its relationships with runoff and sediment movement at the small scale.

Spatial Distribution of Vegetation in Badland Systems

One of the most conspicuous characteristics of vegetation in badland areas is its small-grain spatial heterogeneity, with sharp contrasted patches that match landforms fairly well. This feature is reported by several authors (Butler and Goetz, 1986; Alexander et al., 1994; Guàrdia and Ninot, 1996; Calzolari et al., 1993; Chiarucci et al., 1995; Guàrdia, 1995) and has been explicitly investigated by Lázaro and Puigdefàbregas (1994), Lázaro (1994), and Lázaro et al. (2000a). The main regularities reported by these authors are summarised as follows.

In the divides between gullies, less eroded strips support remains of soils and vegetation that are similar to the regional types on non-gullied hillslopes. On the upper hillslope sectors of gullies, plant communities show slight differentiation, with a higher proportion of pioneer species and changes of composition according to exposure. Backslopes show the strongest differentiation, with very low vegetation density and a prevalence of specialists on moving substrate. Footslopes and pediments are rich in runon-adapted communities that are equipped to withstand sediment deposition and salt accumulation. Finally, stabilised channels and swales host mesic and denser plant communities that are often spatially discontinuous according to the flow conditions of each channel sector.

Most badlands have a long history of activation and stabilisation phases that leave behind successive remains from different ages. This feature offers the opportunity to trace back long-term changes in plant communities, by looking at the botanical composition of samples taken from different-aged remains of the same landform. This was actually performed in the Tabernas badlands, in southeast Spain, by Alexander et al. (1994), who distinguished up to five erosionsedimentation phases that left remnants in the badland landscape. After a botanical survey of the area, they were able to show that relative age was the main factor associated with vegetation differences in the three youngest phases of pediments. The trend with increasing age was a larger total plant cover, a drop in halophytic shrubs, an increase in annual plants, and a smaller but more diverse lichen cover. The factors underlying these changes were the differentiation and leaching of the top soil layers. In the two older classes of pediments, soil is already differentiated and their vegetation was associated with local factors rather than with time.

These findings show that the distribution of badland vegetation is far from random, and is more associated with landforms and time. These two factors determine its complex and often intricate pattern, with sharp boundaries and discontinuities.

More detailed studies of the floristic structure and dominant plant architectures of badland vegetation (Lázaro, 1994; Lázaro et al., 2000a; Guàrdia, 1995; Guerrero, 1998) enabled the species to be grouped into two main classes that were called 'endurers' and 'builders' by Lázaro (1994). Most perennial endurers are able to survive on moving substrates, but as they grow at very low densities their effects on soil evolution and sediment deposition are minimal. They often show prostrate habits and long roots that grow laterally and are able to sprout. Other endurers showing annual behaviour rely on their ability to reproduce themselves in the badland environment. Builders can only be established in fairly stable substrates, but they reach very high densities that help sediment deposition and soil evolution. They often show graminoid morphology, with shallow, fasciculate and very dense root systems. Crustose lichens that cover large proportions of the available surface constitute a group close to builders, which is also associated with quite stable substrates (Lázaro et al., 2000a).

Endurers typically are the most common plants on backslopes undergoing active erosion, while builders grow on more stable or depositional landforms such as pediments, gentle hillslopes or remnants of both on hillslopes that suffer from reactivated erosion. While the builder communities, even when they are few in number, include a large representation of the local flora, endurer communities include only a small number of species drawn from the same local stock.

Lichen crusts are widespread in arid climates (Lázaro et al., 2000a; Yair and Lavee, 1985) in fairly stable upper hillslope convex sectors. In such conditions, soil water storage is very low, because runoff exceeds run-on, and lichens can out-compete annual plants.

These spatial patterns of badland vegetation at the local scale change along climatic gradients. Specific literature on this subject has not been found, but the information available from a transect of field sites along the Mediterranean façade of Spain offers the opportunity of highlighting some regularities.

In the Pyrenean foothills, at the cold-humid end of the Mediterranean transect mentioned above, perennial plants, small shrubs and tussocks constitute the dominant life forms of badland vegetation (Guàrdia, 1995; Guerrero, 1998). In such conditions, soil moisture is high and north-exposed backslopes are less stable than those exposed to the south, because of the geomorphic effect of freezing. Plants living on northern aspects are adapted to both ground instability and harsh winter conditions (Regüés et al., 2000).

In south-east Spain, at the warm-dry end of the transect, crustose terricolous lichens and annual plants are widespread (Alexander and Calvo, 1990; Lázaro, 1994). Soil moisture is low and southerly slopes are the most unstable because of wetting and drying changes and deposition of salts close to the soil surface (Solé et al., 1997). In the Tabernas area, bare soil and eroded soil supporting only very sparse 'endurers' accounts for approximately 33% of the total area. Lichens and living crust can account for 32%, and the rest is more or less densely covered by higher plants, in mosaics of annual and perennial plant patches which act as builders (Cantón, 1999).

Factors Affecting Plant Regeneration and Survival

A review of the constraints on successful establishment of plants in the badland environment will help to explain the patterns of its spatial distribution. These constraints may be grouped in three classes: those that affect soil seed banks, seed germination and seedling survival.

Soil seed banks are replenished by seed yield and dissemination, while they are emptied by germination, seed mortality and seed wash. In most cases, seed yield is fairly irregular over time, because of particular rainfall patterns, or internal physiological factors. Both these factors apply in *mast* years (years in which fruits or seeds are produced largely over average values), although particular rainfall patterns are more common in dry climates and internal physiological factors prevail in humid conditions.

Examples of rainfall-driven mast years in the arid sector of badland distribution have been reported for alpha grass (*Stipa tenacissima*) and annual plants. Mast years for alpha grass correlate with heavy autumn rainfall (Haase et al., 1995) while spring rainfall determines the success or failure of seed yield for annual plants (Espigares Pinilla, 1994).

An example of internally driven mast years may be found in *Retama sphaerocarpa*, a legume bush common in swales and non-incised channels of the badland areas in southeast Spain. This species has a very deep root system (Haase et al., 1996) that ensures a regular water supply through the year. Mast years are therefore determined by the cycles of exhaustion and replenishment of resources triggered by abundant seed yields, rather than by particular rainfall sequences (Gutiérrez, personal communication).

Seed bank depletion by erosion and seed wash has been reported (García-Fayos et al., 1995; García-Fayos and Cerdà, 1997) to be relatively low, between one- and two-thirds of the total seed rain and 10% of the soil seed bank. In general, seed wash cannot be considered a cause of failure of seed supply, although it may affect some species with small or very irregular seed yield. This is the case of species with prevailing vegetative regeneration, such as the tussock grass *Achnatherum calamagrostis* (L.) (Guàrdia, 1995). In contrast, seed wash may cause local increases of the seed bank in depositional landforms in channels or pediments. Seed concentration of the sediments delivered at gully outlets may be larger than that recorded for the hillslopes by a factor of 40 or 50 (García-Fayos et al., 1995).

Information on soil seed bank size in badlands is still scarce, but available figures range between 250 and 1400 seeds m^{-2} (García-Fayos et al., 1995; Guàrdia, 1995; Guàrdia et al., 2000). This reserve is not large, but is sufficient to support germination, which in the cases reported does not reach 10% of the seed bank (Guàrdia, 1995; Guàrdia et al., 2000).

A number of factors affect germination in badland plants, including seed dormancy (Guàrdia, 1995), previous rainfall and temperature sequences (Guàrdia, 1995; Espigares Pinilla, 1994). Soil crusts are claimed to affect germination but no field information is available, and soil salinity has been reported to delay germination in badlands (Maccherini et al., 1996). Most of these factors work through topsoil properties, such as temperature, moisture and salt concentration, which vary spatially over the badland system and so may contribute to the observed spatial pattern of vegetation.

The first months after germination are often critical to the establishment of seedlings. At the Vallcebre field site in the Pyrenean foothills (in the humid climate sector of badland distribution), dissemination and emergence mainly occur in autumn and spring respectively. In such conditions, the first two summers after germination are crucial to seedling establishment: if summer drought occurs in any of these two years, mortality is greater on the more eroded back slopes than on the upper slopes (Guàrdia et al., 1996). Seedling mortality occurs nevertheless all the year round, which implies that mortality is the result of a combination of several factors, such as ground instability, dryness and low winter temperatures (Guàrdia et al., 2000).

In the warm-dry climate sector, annual plants that make up the bulk of badland vegetation germinate with the first autumn storms. However, the time sequence of dry and rainy spells during this season is a strong selection factor that determines the final species composition of the community (Espigares Pinilla, 1994).

Many of the species that make up the vegetation of badlands are mycorrhiza-dependent. This feature has been reported for a number of species in the arid climate sector of southeast Spain, such as *Stipa tenacissima*, *Anthyllis cytisoides*, *Retama sphaerocarpa*, *Stipa capensis*, *Lavandula spica* (Requena et al., 1996). Mycorrhizal infection is crucial for helping nutrient uptake and seedling establishment in poor substrates. However, it is known that soil erosion generally leads to the loss or reduction of mycorrhizal propagules present in the soil (Jasper et al., 1991; Requena et al., 1996); therefore, the lack of inoculum potential for mycorrhiza formation may contribute to the failure of seedling survival on the eroded or recently stabilised badland slopes.

The factors that help germination and seedling establishment also have spatial structure and show most favourable combinations in particular small areas or 'safe sites'. Therefore, it can be anticipated that on eroded badland slopes, mostly colonised by 'endurers', safe-site density is very small and widespread seedling establishment will occur only in particularly favourable years. On the contrary, 'builders' create their own safe site, and therefore increase the probability of success for plant establishment.

This hypothesis has been confirmed by field observations in the Tabernas badland area (Lázaro, 1994; Lázaro et al., 2000b). The botanical composition and cover of annual plant communities at the same set of plots was recorded in a humid and in a dry year. The largest and smallest between-year differences were found in 'endurer' and 'builder' communities, respectively.

Relationships of Vegetation with Runoff and Sediment Movement at the Micro-scale

The information available from Mediterranean badlands enables some general rules on the effects of vegetation on runoff and sediment discharge to be established. Results come mostly from field experiments with micro-plots in different plant cover types using either simulated or natural rainfall (Cantón, 1999; Solé et al., 1997; Calvo et al., 1991a).

'Endurer' populations on backslopes are very sparse and have no significant effect on runoff and sediment movement, which are controlled by other factors such as physical crusts, stone cover, gradient, micro-topography, etc. (Solé et al., 1997; Cantón, 1999).

Results from lichen-covered plots indicate that runoff coefficients are similar to those found on bare ground, while sediment outputs are dramatically reduced. Lichen crusts increase surface rugosity and surface detention of water (Yair et al., 1980). These effects favour initial infiltration and delay the time to runoff (Calvo et al., 1991b; Solé et al., 1997). The final outcome of these features is a desynchronising effect on runoff generation over large areas; and because of this, lichen cover may give high runoff coefficients on the small scale, but these drop abruptly when the contributing areas are bigger (Yair and Lavee, 1985).

This behaviour of lichen stands is very sensitive to cover, and lichen degradation, once it starts, is accelerated by increasing gaps through micro-piping and splash erosion (Yair et al., 1980; Cantón, 1999). Dense patches of 'builders' on hillslopes reflect an increase in infiltration and a decrease in runoff and sediment discharge (Cantón, 1999). The relations of these fluxes with plant cover are negative and often asymptotically non-linear (Solé et al., 1997). Sparse plant cover on upper and less steep slope sectors, more similar to nearby vegetation on non-gullied hillslopes, shows complex interaction with runoff and sediment movement. The effect of vegetation depends on both its density and its spatial structure, and increasing vegetation density causes an exponential decrease of runoff and sediment output. The effect of spatial structure is dynamic and species-specific, and is particularly significant in tussock grasses because they are able to intercept a significant percentage of downhill runoff and sediment flow. Field observations point to interception values of 50% for *Stipa tenacissima* tussocks (Puigdefàbregas and Sánchez, 1996). This lateral interception of sediments interacts with plant growth and helps the formation of banded structures along contour lines that increase the interception effect through a positive feedback. Beyond a certain threshold of downhill sediment flow, spatial structures of vegetation are disrupted, rills are initiated and sediment output rises dramatically (Puigdefàbregas and Sánchez, 1996).

Vegetation in stabilised drainage ways is usually relatively dense, or very dense in some points, and shows high roughness coefficients (Prosser, 1996) that substantially reduce runoff erosivity while increasing infiltration in the channel. This vegetation is very dependent on a water supply from hillslopes, and it has been shown that evapotranspiration from channel stands of *Retama sphaerocarpa* amounts to 130% of rainfall (Domingo et al., in press). For these reasons channel vegetation is prone to local collapses either by piping and mass failures, or by long drought spells, both of which may occur simultaneously and lead to the reactivation of channel incision and thus to erosion in the entire badland system (Nogueras et al., 2000).

A Synopsis on the Functions of Badland Vegetation

Badlands are primarily geomorphic landscapes triggered and maintained by linear incision. Nevertheless, when they develop in areas where climate allows some permanent vegetation, the interaction between vegetation development and hydrological and geomorphic processes becomes the main driver of the system.

When they grow beyond simple gully forms, badlands become complex landscapes, with fine compartmentation between small contiguous areas with diverse soil thickness, erosion and deposition rates, runoff and run-on, as well as sunshine and temperature regimes. This complexity interacts with vegetation, providing a wide range of habitats with different environmental attributes, most of which are characterised by feedback loops between vegetation and geomorphic processes.

The main colonisation trend of vegetation in badlands is similar to the general trends in plant colonisation of barren lands, including biological crusts, herbaceous plants, annuals or perennials depending on climate, shrubs and trees. Changes along this trend occur only if species-specific thresholds of soil stability and water availability have been attained. For example, lichen crusts can only establish themselves if soil movement is small enough, in which case they may persist as a steady state, but poor water availability enables them to out-compete grasses and shrubs.

Density changes in vegetation are determined by such processes as establishment and collapse, which are discontinuous (step-like) and have different constraints. For example, establishment is determined mainly by the density of safe sites, while collapse may be driven by drought spells, sediment wash or mudflows and mass movements. As these processes work at different rates, aggradational and degradational changes are not symmetrical, and hysteresis effects are frequent.

Along a given catena, the most run-on-dependent plant cover types are also likely to be the most sensitive to rainfall change. As these plants are installed in areas close to waterways, they interact with the flow of water and sediments and their collapse may change the hydraulics of the flow, allowing the incision of gullies and reactivating the erosion upstream.

In dry climates the lower rates of the processes driving geomorphic and vegetation changes lead to the persistence of traces of several stabilisation/reactivation cycles. This feature results in heterogeneous and fine-grained spatial patterns, with many relict surfaces with their associated vegetation, and relatively large global plant cover values. On the contrary, in humid zones, processes driving both the evolution of badlands and vegetation recovery work so fast that they remove most of the remnants of previous cycles or phases, and leave a large amount of bare ground or vegetated areas, depending on the current stage of stability or reactivation of linear incision.

10.5 A CLIMATIC CLASSIFICATION OF BADLANDS IN THE MEDITERRANEAN

As a summary of the preceding analysis of badland characteristics and processes in the Mediterranean, a tentative classification of badland landscapes into three main types may be proposed.

1. Arid Badlands

These develop in areas with annual precipitation below 200 mm, where dryness impedes any effective control of vegetation on erosion. They are 'physical' badlands, as vegetation plays no relevant role and geomorphic processes are fully controlled by bedrock and regolith characteristics. Differences between hillslopes of different aspect may exist, but these are related to the direct control of regolith moisture on weathering and erosion processes (Yair and Lavee, 1985). Arid badlands are very old, and their initiation is related to geological controls and drainage net evolution, but not to vegetation degradation by human action. The Zin-Havarim badlands (northern Negev, Israel) provide the best-known example of this type of badlands in the Mediterranean (Yair et al., 1980, 1982; Yair and Lavee, 1985).

2. Semi-arid Badlands

These develop in areas with annual precipitation within the range 200–700 mm, characterised by discontinuous permanent vegetation covers or annuals. Vegetation is able to exert some effective control on geomorphic processes, and the primary control of badland development on vegetation is due to the limitations of water availability imposed by thin regoliths, especially in sunny aspects. Badland landscapes within this range of precipitation are typically asymmetrical (Figure 10.9). The sunny aspects show impoverished or null vegetation cover because of the strong control on water availability effected by radiation, whereas the shady aspects may bear a vegetation cover close to 100% (Kirkby et al., 1990; Solé et al., 1997; Cantón, 1999). Semi-arid badlands are usually old (Wise et al., 1982) and may show the relicts of different phases of stabilisation and reactivation of erosion during their history (Calvo et al., 1991a; Alexander et al., 1994; Nogueras et al., 2000). The initiation of large badland areas is usually due to natural processes, but this precipitation range is very sensitive to gully and badland development as a result of human-induced degradation, especially where traditional agricultural practices concentrate runoff into ditches (Gallart, 1979, 1992). Examples of these badlands are frequent throughout the Mediterranean, the better-known examples being located in various parts of Spain and southern Italy.

Figure 10.9 Oblique aerial photograph of badlands at Tabernas (Almeria, SE Spain), taken from the SW. Observe the conspicuous asymmetry of the landscape

3. Humid Badlands

These develop in areas, usually mountainous in character, with annual precipitation exceeding 700 mm and with frequent rainstorms during the summer. There is enough water to allow dense vegetation cover, including continuous permanent pastures. The growth of vegetation on badland surfaces is checked more by the high erosion rates than by dryness, reclamation with vegetation being feasible especially with the help of some structure used for fixing the regolith (Ballesteros, 1994; Crosaz and Dinger, 1999; Richard and Mathys, 1999). Therefore, the greater dryness of sunny aspects may not be relevant to badland formation, and badlands may be not clearly asymmetrical or may even show reversed asymmetry as freezing, rather than dryness, may control vegetation (Regüés et al., 2000). Humid badlands are usually much younger than arid or semi-arid types, their initiation being related to mass movements (Clotet et al., 1988) or to the degradation of vegetation (Ballais, 1999). The best-known examples of these badlands in Mediterranean regions may be found in the southern Alps (Draix, Haute Provence, France) and in the Pyrenees (Vallcebre, Catalonia, Spain).

REFERENCES

Ahnert, F. 1987. Process-response models of denudation at different spatial scales. *Catena Supplement*, 10, 31–50.

Alexander, D. 1982. Differences between calanchi and biancane badlands in Italy. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, 71–87.

Alexander, R.W. and Calvo, A. 1990. The influence of lichens on slope processes in some Spanish badlands. In J.B. Thornes (Ed.) *Vegetation and Erosion*. Wiley, Chichester, 385–398.

Alexander, R.W., Harvey, A.M., Calvo, A., James, P.A. and Cerda, A. 1994. Natural stabilization mechanisms on badland slopes: Tabernas, Almería, Spain. In A.C. Millington and K. Pye (Eds) *Environmental Change in Drylands: Biogeographical and Geomorphological Perspectives*. John Wiley and Sons, 85–111.

Ballais, J.L. 1999. Apparition et évolution de roubines à Draix. In N. Mathys (Ed.) *Les bassins versants expérimentaux de Draix, laboratoire d'étude de l'érosion en montagne*. Cemagref, Antony, 235–245.

Ballesteros, R. 1994. *Efecte dels factors locals y de la fertilitat en una experiència de revegetació en un àrea de badlands de la conca de l'Alt Llobregat*. Treball Final de Carrera, Escola Superior d'Agricultura de Barcelona (unpublished).

Benito, G., Gutiérrez, M. and Sancho, C. 1992. Erosion rates in badlands areas of the Central Ebro Basin (NE Spain). *Catena*, 19, 262–286.

Berrad, F., García-Rossell, L. and Martín-Vellejo, M. 1994. Les propriétés géomécaniques, un facteur de contrôle de l'érosion: Cas d'une zone aride su sudeste espagnol. In Oliverira, Rodrigues, Coelho and Cunha (Eds) *7th International IAEG Congress*, Balkema, Rotterdam, 331–338.

Bouma, N.A. and Imeson A.C. 2000. Investigation of relationships between measured field indicators and erosion processes on badland surfaces at Petrer, Spain. *Catena*, 40, 147–171.

Bryan, R.B. and Yair, A. (Eds) 1982a. *Badland Geomorphology and Piping*. GeoBooks, Norwich, 408pp.

Bryan, R.B. and Yair, A. 1982b. Perspectives on studies of badland geomorphology. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, 1–12.

Bryan, R.B., Yair, A. and Hodges, W.K. 1978. Factors controlling the initiation of runoff and piping in Dinosaur Provincial Park badlands, Alberta, Canada. *Zeitschrift für Geomorphologie Supplement Band*, 29, 151–168.

Butler, J. and Goetz, H. 1986. Vegetation and soil-landscape relationships in the North Dakota badlands. *The American Midland Naturalist*, 116(2), 378–386.

Calvo, A., Harvey, A.M. and Paya-Serrano, J. 1991a. Processes interactions and badland development in SE Spain. In M. Sala, J.L. Rubio and J.M. García-Ruiz (Eds) *Soil Erosion Studies in Spain*, pp. 75–90, Geoforma Ed., Logroño.

Calvo, A., Harvey, A.M., Paya-Serrano, J. and Alexander, R.W. 1991b. Response of badland surfaces in SE Spain to simulated rainfall. *Cuaternario y geomorfología*, 5, 3–14.

Calzolari, C., Ristori, J., Sparvoli, E., Chiarucci, A. and Soriano, M.D. 1993. Soils of biancana badlands: distribution, characteristics and genesis in Beccanello Farm (Tuscany, Italy). *Quaderni di Scienza del Suolo*, 5, 119–141.

Campbell, I.A. 1974. Measurement of erosion on badlands surfaces. *Zeitschrift für Geomorphologie Supplement Band*, 21, 122–137.

Campbell, I.A. 1982. Surface morphology and rates of change during a ten-year period in the Alberta badlands. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 221–237.

Campbell, I.A. 1989. Badlands and badland gullies. In D.S.G. Thomas (Ed.) *Arid Zone Geomorphology*. Belhaven/Halsted Press, London, 159–183.

Cantón, Y. 1999. *Efectos hidrológicos y geomorfológicos de la cubierta y propiedades del suelo en paisaje de cárcavas*. Unpublished PhD thesis, Universidad de Almeria, Spain, 394pp.

Cantón,Y., Solé-Benet, A., Queralt, I. and Pini, R. 2001.Weathering of a gypsum-calcareous mudstone under semi-arid environment at Tabernas, SE Spain: laboratory and field-based experimental approaches. *Catena* (in press).

Castelltort, X. 1995. *Erosió, transport y sedimentació fluvial com a integració dels processos geomorfològics d'una conca. (Conca de Cal Rodó, Alt Llobregat.)* PhD Thesis, U. Barcelona, 235pp.

Clotet, N. and Gallart, F. 1986. Sediment yield in a mountainous basin under high Mediterranean climate. *Zeitschrift für Geomorphologie Supplement Band*, 60, 205–216.

Clotet, N., Gallart, F. and Balasch, J. 1988. Medium term erosion rates in a small scarcely vegetated catchment in the Pyrenees. *Catena Supplement*, 13, 37–47.

Crosaz, Y. and Dinger, F. 1999 Mesure de l'érosion sur ravines élémentaires et essais de végétalisation. Bassin versant expérimental de Draix. In N. Mathys (Ed.) *Les bassins versants expérimentaux de Draix, laboratoire d'étude de l'érosion en montagne*. Cemagref, Antony, 103–118.

Chiarucci, A., De Dominicis, V., Ristori, J. and Calzolari, C. 1995. Biancana badland vegetation in relation to morphology and soil in Orcia calley, central Italy. *Phytocoenologia*, 25(1), 65–87.

Domingo, F., VillaGarcía, L., Puigdefàbregas, J., Boer, M. and Alados-Arboledas, L. (in press). Assessing lateral water inputs to vegetation of an ephemeral river in semi-arid climate through rainfall-evapotranspiration relationships. *Agricultural Forest Meteorology*.

Egels, Y., Kasser, M., Meunier, M., Muxart, T. and Guet, C. 1989. Utilisation des mésures topographiques (Photogrammétrie terrestre et télémetrie sans réflecteur) pour la mesure de l'érosion de petits bassins versants expérimentaux et comparaison avec les mesures de transport solide à l'émissaire. *Bassins Versants expérimentaux de Draix, Compte rendu de Recherche no 2 en érosion et hydraulique torrentielle*. CEMAGREF, ONF-RTM, 3-25.

Emerson, V.V. 1967. A classification of soil aggregates based on their consistency in water. *Australian Journal of Soil Research*, 5, 47–57.

Espigares Pinilla, T. 1994. *Fluctuaciones en la dinamica de pastizales anuales mediterraneos: El papel de los factores meteorologicos en el momento de la regeneracion*. Tesis Doctoral, Universidad Autónoma de Madrid.

Fairbridge, R.W. 1968. *Encyclopedia of Geomorphology*. Dowden, Hutchinson and Ross, Inc. Pennsylvania, USA.

Farres, P. 1978. The role of time and aggregate size in the crusting process. *Earth Surface Processes and Landforms*, 3, 243–254.

Gallart, F. 1979. Observaciones sobre la geomorfología dinámica actual en la Conca d'Òdena (Alrededores de Igualada, provincia de Barcelona). In J. Muñoz, T. Aleixandre and J. Gallardo (Eds) *Actas de la III Reunión del Grupo Español de Trabajo del Cuaternario*. CSIC, Madrid, 123–134.

Gallart, F. 1992. Estudi Geomorfològic de la Conca d'Odena. *L'Estrat*, 3 (monogràfic), 9–45, Igualada (Barcelona).

Gallart, F., Latron, J. and Regüés, D. 1998. Hydrological and sediment transport processes in the research catchments of Vallcebre (Pyrenees). In J. Boardman and D. Favis-Mortlock (Eds) *Modelling Erosion by Water*. Springer-Verlag NATO-ASI Series I-55, Berlin, 503–511.

García-Fayos, P. and Cerdà, A. 1997. Seed losses by surface wash in degraded Mediterranean environments. *Catena*, 29, 73–83.

García-Fayos, P., Recatala, T.M., Cerdà, A. and Calvo, A. 1995. Seed population dynamics on badland slopes in southeastern Spain. *Journal of Vegetation Science*, 6, 691–696.

Gerits, J.J.P., Imeson, A.C. and Verstraeten, J.M. 1986. Chemical thresholds and erosion in saline and sodic materials. In F. López-Bermúdez and J. Thornes (Eds) *Estudios Sobre la Geomorfología del Sur de España*. Murcia, 71–74.

Gerits, J., Imeson, A.C., Verstraeten J.M. and Bryan, R.B. 1987. Rill development and badland regolith properties. *Catena Supplement*, 8, 141–160.

Gomer, D. 1995. *Écoulements et érosion dans des petits bassins-versants à sols marneux sous climat semi-aride méditerranéen*. Published by: 'Projet pilote d'aménagement integré du bassin versant de l'oued Mina, c/o Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, D-65726 Eschborn'. 207 pp + annexes.

Goudie, A.S. 1990. Weathering processes. In D.S.G. Thomas (Ed.) *Arid Zone Geomorphology*. Belhaven/ Halsted Press, London, 11–24.

Guàrdia R. 1995. *La colonitzacio vegetal de les arees erosionades de la conca de La Baells (Alt Llobregat)*. Doctoral Thesis, University of Barcelona.

Guàrdia, R. and Ninot, J.M. 1996. Distribution of plant communities in the badlands of the upper Llobregat basin (southeastern Pyrenees). *Studia Geobotanica*, 12, 83–103.

Guàrdia, R., Alcantara, C. and Ninot, J.M. 1996. Dinàmica anual de l'emergència de plàntules a les àrees aixaragallades de la conca de Vallcebre (Alt Llobregat). *Folia Botanica Miscellanea*, 10, 211–229.

Guàrdia, R., Gallart, F. and Ninot, J.M. 2000. Soil seed bank and seedling dynamics in badlands of the upper Llobregat basin (Pyrenees). *Catena*, 40, 173–187.

Guerrero, J. 1998. *Respuestas de la vegetación y de la morfdología de las plantas a la erosion del suelo. Valle del Ebro y Prepirineo atagonés*. Publicaciones del Consejo de Protección de la Naturaleza de Aragón. 12. Zaragoza, 231pp.

Gutiérrez, M., Benito, G. and Rodríguez, J. 1988. Piping in badland areas on the middle Ebro basin, Spain. *Catena Supplement*, 13, 49–60.

Gutiérrez, M., Sancho, C., Desir, G., Sirvent, J., Benito, G. and Calvo, A. 1995. *Erosión hídrica en terrenos arcillosos y yesíferos de la Depresión del Ebro*. ICONA, Universidad de Zaragoza, 389pp.

Haase, P., Pugnaire, F.I. and Incoll, L.D. 1995. Seed production and dispersal in the semi-arid tussock grass *Stipa tenacissima* (L.) during masting. *Journal of Arid Environments*, 31, 55–65.

Haase, P., Pugnaire, F.I., Fernández, E.M., Puigdefàbregas, J., Clark, S.C. and Incoll, L.D. 1996. An investigation of rooting depth of the semi-arid shrub *Retama sphaerocarpa* (L.) Boiss. by labelling of ground water with a chemical tracer. *Journal of Hydrology*, 177, 23–31.

Harvey, A. 1982. The role of piping in the development of badlands and gully systems in south-east Spain. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 317–335.

Harvey, A. 1987. Patterns of Quaternary aggradational and dissectional landform development in the Almeria region, southeast Spain: a dry region tectonically-active landscape. *Die Erde*, 118, 193–215.

Harvey, A.M. and Calvo, A. 1989. Distribution of badlands in SE Spain: implications of climatic change. In A.C. Imeson and De Groot (Eds) *Landscape-ecological impact of climatic change*, discussion report on Mediterranean region.

Hodges, W.K. and Bryan, R.B. 1982. The influence of material behavior on runoff initiation in the Dinosaur Badlands, Canada. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 13–46.

Howard, A.D. 1994. Badlands. In A.D. Abrahams and A.J. Parsons (Eds) *Geomorphology of Desert Environments*. Chapman & Hall, London, 213–242.

Imeson, A. 1986. Investigating volumetric changes in clayey soils related to subsurface water movement and piping. *Zeitschrift für Geomorphologie Supplement Band*, 60, 115–130.

Imeson, A.C. and Verstraeten, J.M. 1988. Rills on badland slopes: a physico-chemically controlled phenomenon. *Catena Supplement*, 12, 139–150.

Imeson, A.C. and Verstraeten, J.M. 1989. The microaggregation and erodibility of some semi-arid mediterranean soils. *Catena Supplement*, 14, 11–24.

Imeson, A.C., Kwaad, F.J.P.M. and Verstraeten, J.M. 1982. The relationship of soil physical and chemical properties to the development of badlands in Morocco. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 47–70.

Jasper, D.A., Abbot, L.K. and Robson, A.D. 1991. The effect of soil disturbance on vesicular-arbuscular mycorrhizal fungi in soils from different vegetation types. *New Phytologist*, 118, 471–476.

Kirkby, M.J. 1976. Hydrological slope models. The influence of climate. In E. Derbyshire (Ed.) *Geomorphology and Climate*. John Wiley and Sons, Chichester, 247–267.

Kirkby, M.J., Atkinson, K. and Lockwood, J. 1990. Aspect, vegetation cover and erosion on semi-arid hillslopes. In J. Thornes (Ed.) *Vegetation and Erosion*. Wiley, Chichester, 25–39.

Lambe, T.W. 1951. *Soil Testing for Engineers*. John Wiley & Sons, New York, 165pp.

Langbein, W.B. and Schumm, S.A. 1958. Yield of sediment in relation to mean annual precipitation. *Transactions of the American Geophysical Union*, 39, 1076–1084.

Lázaro, R. 1994. *Relaciones entre vegetación y geomorfología en el área acarcavada del Desierto de Tabernas*. Unpublished PhD thesis. Universidad de Valencia.

Lázaro, R. and Puigdefàbregas, J. 1994. Distribución de la vegetación terofítica en relacion con la geomorfologia en areas acarcavadas cerca de Tabernas (Almeria). *Monografías de Flora y Vegetación Béticas*, 7-8, 127–154.

Lázaro, R., Alexander, R. and Puigdefàbregas, J. 2000a. Cover distribution patterns of lichens, annuals and shrubs in the Tabernas Desert, Almería, Spain. In R.W. Alexander and A.C. Millington (Eds) *Vegetation Mapping: From Patch to Planet*. Wiley & Sons, Chichester, 19–40.

Lázaro, R., Rodrigo, F.S., Gutiérrez, L., Domingo, F. and Puigdefàbregas, J. 2000b. Analysis of a thirty year rainfall record (1967–1997) from semi-arid SE Spain: a plant ecological perspective. *Journal of Arid Environments* (in press).

Lecompte, M., Lhenaff, R. and Marre, A. 1996. Premier bilan de six années de mesures sur l'ablation des roubines des Baronnies méridionales (Préalpes françaises du sud). *Revue de Géographie Alpine*, 1996(2), 11–16.

López-Bermúdez, F. and Romero Díaz, M.A. 1989. Piping erosion and badland development in SE Spain. *Catena Supplement*, 14, 59–74.

Maccherini, S., Chiarucci, A., Torri, D., Ristori, J. and De Dominicis, V. 1996. Influence of salt content of pliocene clay soil on the emergence of six grasses. *Israel Journal of Plant Sciences*, 44, 29–36.

Martín-Penela, A.J. 1994. Pipe and gully systems development in the Almanzora Basin (SE Spain). *Z. Geomorph.* N.F., 38(2), 207–222.

Meunier, M., Cambon, Olivier, Mathys, N., Combes, 1987. *Bassins versants expérimentaux de Draix.* Compte rendu de recherche no. 1 en érosion et hydraulique torrentielle. CEMAGREF-ONF-RTM.

Nogueras, P., Burjachs, F., Gallart, F. and Puigdefàbregas, J. 2000. Recent gully erosion in the El Cautivo badlands (Tabernas, SE Spain). *Catena*, 40, 203–215.

Oostwoud Wijdenes, D.J. and Ergenzinger, P. 1998. Erosion and sediment transport on steep marly hillslopes, Draix, Haute-Provence, France. An experimental field study. *Catena*, 33, 179–200.

Pardini, G. 1996. *Evoluzione temporale della microtopografia superficiale, della micromorfologia e della struttura in relazione ai processi di meteorizzazione nelle marne smectitiche di Vallcebre.* Ph.Dr Thesis. Facultat de Geologia, Universitat de Barcelona (unpublished).

Pardini, G., Pini, R., Barbini, R., Regüés, D., Plana, F. and Gallart, F. 1995. Laser elevation measurements of a smectite-rich mudrock following freeze-thawing and wet-drying cycles. *Soil Technology*, 8, 161–175.

Pardini, G., Vigna Guidi, G., Pini, R., Regüés, D. and Gallart, F. 1996. Structural changes of smectite-rich mudrocks experimentally induced by freeze–thawing and wetting–drying cycles. *Catena*, 27, 149–165.

Puigdefàbregas, J. and Sánchez, G. 1996. Geomorphological implications of vegetation patchiness on semi-arid slopes. In M.G. Anderson and S.M. Brooks (Eds) *Advances in Hillslope Processes*, vol. 2. Wiley & Sons, Chichester, 1027–1060.

Prosser, I.P. 1996. Thresholds of channel initiation in Historical and Holocene Times, Southeastern Australia. In M.G. Anderson and S.M. Brooks (Eds) Advances in Hillslope Processes, vol. 2. Wiley & Sons, Chichester, 687–708.

Regüés, D., Guàrdia, R. and Gallart, F. 2000. Geomorphic agents versus vegetation spreading as causes of badland occurrence in a Mediterranean subhumid mountainous area. *Catena*, 40, 173–187.

Regüés, D., Pardini, G. and Gallart, F. 1995. Regolith behaviour and physical weathering of clayey mudrock as dependent on seasonal weather conditions in a badland area at Vallcebre, Eastern Pyrenees. *Catena*, 25, 199–212.

Regüés, D., Llorens, P., Pardini, G., Pini, R. and Gallart, F. 1993. Physical weathering and regolith behaviour in a high erosion rate badland area at the Pyrenees: research design and first results. *Pirineos*, 141/142, 63–84.

Requena, N., Jeffries, P. and Barea, J.M. 1996. Assessment of natural mycorrhizal potential in a desertified semiarid ecosystem. *Applied and Environmental Microbiology*, 62(3), 842–847.

Richard, D. and Mathys, S. 1999. Historique, contexte technique et scientifique des BVRE de Draix. Caractéristiques, données disponibles et principaux résultats acquis au cours de dix ans de suivi. In N. Mathys (Ed.) *Les bassins versants expérimentaux de Draix, laboratoire d'étude de l'érosion en montagne.* Cemagref, Antony, 11–28.

Scoging, H. 1982. Spatial variations in infiltration, runoff and erosion on hillslopes in semi-arid Spain. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 89–112.

Scheidegger, A.E., Schumm, S.A. and Fairbridge, R.W. 1968. Badlands. In R. Fairbridge (Ed.) *Encyclopedia of Geomorphology*. Dowden, Hutchinson and Ross, Inc., USA, 43–48.

Scheidig, A. 1934. *Der Löss (Loess)*. Dresden, 233pp.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bulletin of the Geological Society of America*, 67, 597–646.

Sirvent, J., Gutiérrez, M. and Desir, G. 1996. Erosión e hidrología de áreas acarcavadas. In T. Lasanta and J.M. García-Ruiz (Eds) *Erosión y Recuperación de Tierras en Áreas Marginales*. Instituto de Estudios Riojanos – SEG, 109–135.

Sirvent, J., Desir, G., Gutiérrez, M. and Sancho, C. 1997. Erosion rates in badland areas recorded by collectors, erosion pins and profilometer techniques (Ebro basin, NE Spain). *Geomorphology*, 18(2), 61–75.

Solé, A., Josa, R., Pardini, G., Aringhieri, R., Plana, F. and Gallart, F. 1992. How mudrock and soil physical properties influence badland formation at Vallcebre Pre-Pyrenees (NE Spain). *Catena*, 19(3-4), 287–300.

Solé, A., Calvo, A., Cerdà, A., Lázaro, R., Pini, R. and Barbero, J. 1997. Influence of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain). *Catena*, 31, 23–38.

Stocking, M.A. 1988. Assessing vegetative cover. In R. Lal (Ed.) *Soil Erosion Research Methods*. Soil and Water Conservation Society, Ankeny, Iowa, 163–185.

Taylor, R.K. and Smith, T.J. 1986. The engineering geology of clay minerals: swelling, shrinking and mudrock breakdown. *Clay Minerals*, 21, 235–260.

Terzaghi,K. and Peck, R.B. 1967. *Soil Mechanics in Engineering Practice*, 2nd Edn. John Wiley & Sons, New York.

Torri, D. and Bryan, R. 1997. Micropiping processes and biancana evolution in southeast Tuscany, Italy. *Geomorphology*, 557.

Torri, D., Colica, A. and Rockwell, D. 1994. Preliminary study of the erosion mechanisms in a biancana badland (Tuscany, Italy). *Catena*, 23, 281–294.

Wise, S.M., Thornes, J.B. and Gilman, A. 1982. How old are the badlands? A case study from south-east Spain. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*. GeoBooks, Norwich, England, 259–278.

Wolman, M.G. and Gerson, R. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth Surface Processes and Landforms*, 3, 189–208.

Yair, A., Goldberg, P. and Brimer, B. 1982. Long term denudation rates in the Zin-Havarim badlands, northern Negev, Israel. In R.B. Bryan and A. Yair (Eds) *Badland Geomorphology and Piping*, GeoBooks, Norwich, England, 279–291.

Yair, A., Lavee, H., Bryan, R.B. and Adar, E. 1980. Runoff and erosion processes and rates in the Zin valley badlands, northern Negev, Israel. *Earth Surface Processes and Landforms*, 5, 205–225.

Yair, A. and Lavee, H. 1985. Runoff generation in arid and semiarid zones. In M.G. Anderson and T.P. Burt (Eds) *Hydrological Forecasting*. Wiley, Chichester, 183–220.

Yoder, R.R. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *Journal of the American Society of Agronomy*, 28, 337–351.