MONITORING AND MODELLING DYNAMIC ENVIRONMENTS

Edited by Alan P. Dykes, Mark Mulligan and John Wainwright

WILEY Blackwell

Monitoring and Modelling Dynamic Environments

(A Festschrift in Memory of
Professor John B. Thornes)

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GEOMORPHOLOGY
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1 2015

This book is dedicated to the memory of Professor John B. Thornes – geographer, geomorphologist, leader, mentor, colleague and friend.

Photograph courtesy Rosemary Thornes.

Contents

PART B

List of contributors

Ashraf Afana
Department of Geography
Durham University
South Road, Durham, UK

Irasema Alcántara-Ayala
Instituto de Geografía
Universidad Nacional Autónoma
de México (UNAM)
Coyoacan, Mexico

Gabriel del Barrio
Estación Experimental de Zonas Áridas (EEZA)
CSIC, Cañada de San Urbano
Almeria, Spain

Louise J. Bracken
Department of Geography
Durham University
South Road, Durham, UK

Jane Brandt
Fondazione MEDES
Sicignano degli Alburni (SA), Italy

Denys Brunsden
Vine Cottage
Seatown, Dorset, UK

Tim Burt
Department of Geography
Durham University
South Road, Durham, UK

Artemi Cerdà
SEDER – Soil Erosion and Degradation
Research Group
Department of Geography
University of Valencia
Valencia, Spain

Thomas J.B. Dewez
Direction of Risks and Prevention – BRGM – French
Geological Survey
Orléans-la-Source, France

Alan P. Dykes
School of Civil Engineering and Construction
Kingston University
Penrhyn Road, Kingston upon Thames, UK

Carolyn F. Francis
Halcrow Group Ltd,
a CH2M HILL Company
Swindon, UK

Nichola Geeson
Fondazione MEDES
Sicignano degli Alburni (SA), Italy

Antonio Giménez-Morera
Departamento de Economía y Ciencias Sociales
Escuela politécnica superior de Alcoy
Universidad Politécnica de Valencia
Alicante, Spain

Ken Gregory
Department of Geography
University of Southampton
Southampton, UK

Janet Hooke
Department of Geography and Planning
School of Environmental Sciences
University of Liverpool
Liverpool, UK

Antonio Jordan
MED_Soil Research Group
Department of Crystallography, Mineralogy and
Agricultural Chemistry
University of Seville
Seville, Spain

Saskia Keesstra
Soil Physics and Land Management Group
Wageningen University
Wageningen, the Netherlands

Mike Kirkby
School of Geography
University of Leeds
Woodhouse Lane, Leeds, UK

Andrew T. Lowe
Halcrow Group Ltd, a CH2M HILL Company
a CH2M HILL Company
Warrington, UK

Jenny Mant
River Restoration Centre
Cranfield University Campus
Bedford, UK

Matthew Marsik
Land Use and Environmental
Change Institute
University of Florida
Gainesville, FL, USA

Jorge Mataix-Solera
Environmental Soil Science Group
Department of Agrochemistry
and Environment
Miguel Hernández University
Alicante, Spain

Mark Mulligan
Department of Geography
King's College London
London, UK

Agata Novara
Dipartimento dei Sistemi Agro-ambientali
University of Palermo
Palermo, Italy

Paulo Pereira
Department of Environmental Policy
Mykolas Romeris University
Vilnius, Lithuania

Marvin Quesada
Departamento de Ciencias Sociales
Universidad de Costa Rica Sede Occidente
San Ramón, Costa Rica

Asunción Romero Díaz
Department of Geography
University of Murcia
Murcia, Spain

José Damián Ruíz Sinoga
Department of Geography
University of Málaga
Málaga, Spain

Leszek Starkel
Department of Geomorphology and Hydrology
Institute of Geography,
Polish Academy of Sciences
Krakow, Poland

Iain S. Stewart
Centre for Research in Earth Sciences, School
of Geography, Earth, & Environmental Sciences
University of Plymouth
Plymouth, UK

John Wainwright
Department of Geography
Durham University
South Road, Durham, UK

Glenn Watts
Evidence Directorate, Environment Agency
Bristol, UK
and
Department of Geography
King's College London
London, UK

Peter Waylen
Department of Geography
University of Florida
Gainesville, FL, USA

About the editors

Alan P. Dykes is currently a senior lecturer in civil engineering at Kingston University, London. He obtained a geography degree from the University of Bristol in 1990, and he went on to undertake research for his PhD under John Thornes' supervision, transferring to King's College London when John moved to King's. His PhD project, *Hydrological controls on shallow mass movements and characteristic slope forms in the tropical rainforest of Temburong District, Brunei*, was part of the 'Brunei Rainforest Project' organised by the Royal Geographical Society (RGS) with the Universiti Brunei Darussalam. Throughout several years at Huddersfield University and more recently Kingston University, Alan has used his wide-ranging expertise in fieldwork, geotechnical laboratory testing and computer modelling to focus his research on landslides/slope instability and hydrological systems in landscape contexts as diverse as Ecuador, Indonesia, Iran, Ireland, Italy, Malaysia, Malta and Mexico and is now a leading authority on peatland instability and failure.

Mark Mulligan is currently a reader in geography at King's College London. He obtained a geography degree from the University of Bristol in 1991, which included fieldwork with the 'Brunei Rainforest Project', then moved to King's College London to undertake a PhD on '*Modelling hydrology and vegetation change in a degraded semi-arid environment*', supervised by John Thornes. Mark remained at King's College London as a permanent member of academic staff following his PhD, apart from a year on research secondment at the Istituto di Botanica, Università di Napoli, Italy, and in 2004 was awarded the *Gill Memorial Award* of the Royal Geographical Society – Institute of British Geographers for 'innovative monitoring and modelling' of environmental systems. Mark works on a variety of topics in the areas of environmental spatial policy support, ecosystem service modelling and understanding environmental change, at scales from local to global and with a particular emphasis on tropical forests in Latin America and semi-arid drylands in the Mediterranean.

John Wainwright is a professor in physical geography at Durham University. He completed a PhD on '*Erosion of semi-arid archaeological sites: A study in natural formation processes*' at the University of Bristol, supervised by John Thornes, in 1991. After brief spells at Keele and Southampton universities, John W. took up a permanent position at King's College London, becoming a professor within 10 years and in 1999 being awarded the *Gordon Warwick Award* of the British Geomorphological Research Group for his innovative work in the understanding of past and present semi-arid environments. John subsequently moved to Sheffield University, including 3 years as a visiting professor at Université Louis Pasteur, Strasbourg, then to Durham University in 2011. He has undertaken extensive field research, especially in drylands in the Mediterranean, the US Southwest and sub-Saharan Africa, and links the data to theory using computer modelling combined with results from laboratory experiments on slope and channel processes.

Like John Thornes, Alan Dykes and John Wainwright are originally from the county of Yorkshire in the north of England. Mark is from a little further south.

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CHAPTER 1

Introduction – Understanding and managing landscape change through multiple lenses: The case for integrative research in an era of global change

Alan P. Dykes[1], Mark Mulligan[2] and John Wainwright[3]

[1] *School of Civil Engineering and Construction, Kingston University, Kingston upon Thames, UK*

[2] *Department of Geography, King's College London, London, UK*

[3] *Department of Geography, Durham University, Durham, UK*

> *The twenty-first century is when everything changes. And we must be ready.*
>
> *(BBC 2006)*

The world is changing. It has always been changing, as internal geophysical processes drive the tectonic systems that slowly rearrange the distributions of land masses and oceans and external influences such as orbital eccentricities alter the Earth's climate. Over hundreds of millions of years, the physical and ecological environments at any given location on land have been shaped and reshaped by natural then, from the late Pleistocene onwards, increasingly by human processes – so much so that some argue for a new geological epoch (the Anthropocene) in recognition of this (see Steffen et al. 2011; Brown et al. 2013). Our recognition of different kinds of impacts and implications of landscape changes has developed in parallel with the increasing rates of industrialisation of the last 250 years (Hooke 2000; Wilkinson 2005; Montgomery 2007). Humans are highly inventive in providing technological 'solutions' to feeding, watering and providing energy for ever-increasing populations, but this inventiveness does not always produce resilient or sustainable solutions. Indeed, it is often only when we are highly dependent upon these technologies that we begin to understand their negative effects on the environment that also sustains us. This is a reflection of both scientific advancement throughout the period and the increasing impacts on landscapes of the expanding industrial activities, including the industrialisation of agriculture, water and energy provision. However, although we know some of the impacts of these technologies on natural landscapes and the 'ecosystem services' that they provide, many aspects of the natural functioning of these landscapes remain uncertain.

The continually increasing population of the Earth has inevitably led to the expansion of anthropic modification of landscapes into increasingly marginal (in terms of primary productivity) or unstable (in terms of ecology and/or geomorphology) lands. The associated risks have driven much of the agricultural and geomorphological research that has provided the

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basis for the management of landscapes undergoing such changes. However, towards the late 20th century, there developed a greater awareness of the potential for long-term catastrophic losses of productive agricultural lands as a consequence of inadequate or inappropriate management (e.g. Montgomery 2007), usually stemming from inadequate relevant scientific knowledge – or the lack of communication, or application, of that knowledge in policy formulation. The early years of the 21st century have also focused attention on the potentially increasing risks of natural hazards arising from regional manifestations of anthropic, global climate change. Extreme climate events lead to floods and landslides and wind storms, all of which cause losses of life, property and livelihood, but they may also lead to more chronic adverse impacts on societies through losses of land productivity – and these effects may be exacerbated by inappropriate land management strategies and agricultural practices.

John B. Thornes recognised the importance of good basic and applied geomorphological knowledge for the sound management of landscape change relatively early. Many of his ideas were developed from his early research experiences in central Spain in the mid-1960s, although his work on the particular problems of semi-arid environments did not begin until 1972 (e.g. Thornes 1975). Fundamental to his work was the development of modelling approaches for understanding geomorphological processes and systems in parallel with the implementation of intensive field data collection methodologies to support the parameterisation of the models. Perhaps crucially, he identified the need to measure not only 'descriptive' parameters such as morphology or particle size – typical of early quantitative geomorphology – but also landscape properties and processes that would allow quantification of the key geomorphological issues of spatial *and temporal* scale and variability. As such, he was a key player in the adoption of both monitoring and modelling approaches in geomorphological research and a leader in the explicit integration of these approaches and in the application of the findings to management policy and practice. For John, geomorphology included climate, hydrology and vegetation and their interactions with geomorphological processes and thus forms and their dynamics. As well as the management of modern processes, this interaction between process and form also informed John's understanding of past environments, particularly in his work on palaeohydrology and geoarchaeology.

Monitoring, modelling and management

Monitoring in environmental science is the process of keeping track, over time, of how one or more material properties or system states behave, based on repeated observations and measurements. It underpins the empirical understanding of environmental processes by observation of their consequences. For example, investigation of micro-scale controls on the process of soil matrix throughflow could require monitoring of water temperature (material property), soil water content and instantaneous flow velocity (static and dynamic system states, respectively). In geomorphology, many material properties are effectively constant at the timescale of a research project, but for other variables, the monitoring data required and hence the method by which they are obtained depend on the spatial and temporal scales of the problem being investigated. Technological advances over the last 30–40 years have increasingly expanded the range of what can be measured (i.e. parameter/variable type and scale) and at what frequency, although in some cases there remain constraints. For example, satellites cannot yet provide both very high temporal frequency and very high spatial resolution data – although most applications of this approach such as monitoring land-use change do not require high frequencies of repeated observations, and rapid developments in UAV techniques are addressing some of these limitations at local scales. Most field monitoring takes place at points, and the cost of equipment and labour to maintain field monitoring 'stations' means that there are often relatively few of these, so that significant interpolation is required for landscape-scale analysis. However, it must be remembered that remotely sensed observations are proxies of the properties or system states of interest and must be grounded in field measurement.

Modelling is the process of representing or displaying something that cannot otherwise be experienced, through abstraction of reality and representation in the form of a conceptual, mathematical or physical model. John Thornes was one of the pioneers of mathematical models in geomorphology, which are increasingly used as representations of geomorphic systems. They are usually used as a way of evaluating conceptual models of components of a system such as a specific process or a topographic subsystem representing a set of processes; furthermore, today's office PCs can typically carry out hundreds of simulations using highly sophisticated models and produce the results before the morning coffee break. However, as with any investigation, the type and formulation of the model necessarily depends on the purpose of the research and, critically, on the quality and quantity of data that may be available to set up the model and evaluate its outputs (Mulligan and Wainwright 2004). John always understood that the geomorphological processes of greatest interest to him existed within a complex context. Over his career, through his own research and that which he supervised, collaborated with or helped to fund, he tried to ensure that as much of the relevant contextual complexity as was useful, was included. In his modelling of erosion, he started by defining and representing the process itself (Embleton and Thornes 1979). Subsequently, he introduced interactions with terrain, climate and geology (Thornes and Alcántara-Ayala 1998), then vegetation (Thornes 1990) and finally animals (Thornes 2007). All of this was done with a clear focus on the socio-economic context and the policy outcomes (Brandt and Thornes 1996; Geeson et al. 2003) and an understanding of the role of time (Thornes and Brunsden 1977) and of history (Wainwright and Thornes 2003).

The degradation of agricultural lands in the Mediterranean region has been investigated at all spatial scales, from small experimental plots on hillslopes to remote sensing of the entire region. One of the major challenges has been to integrate not only the monitoring data with the modelling of erosion processes and changing state of the landscape system but also the findings from different scales of investigation into regional-scale, operational management tools. John Thornes was quick to embrace the possibilities presented by GIS technology (particularly digital elevation models) and satellite remote sensing and the integration of such techniques with smaller scale field studies and process or system models. Indeed, combining field and remote sensing-based monitoring with modelling was one of John's key foci during the latter part of his career, particularly in the European Mediterranean. He then led the development of the conceptual framework that ultimately led to the GIS-based and web-based, management-focused tools that came later. These will undoubtedly continue to be refined, not least to accommodate the threats to sustainability deriving from new technologies and/or revealed by ongoing monitoring programmes.

Management is used here in its broadest sense to refer to all levels of application of research findings by different agents, ranging from individual farmers and local communities through to regional managers and national/international policymakers such as the US federal government or the European parliament. We also use it to include all types of management, from details of how an individual field with particular soil types and rainfall patterns should be ploughed and then planted up to multi-decadal plans for new water resource infrastructure. The outputs of several of the desertification research projects initiated by John Thornes and outlined in this book provided outputs that are designed to be applied at all scales of application including EU-scale funding decisions. Application of research so as to have tangible effects on individual farmers, governmental policies and/or any other level of governance or commercial activity would constitute what is now generically referred to as 'impact' in the UK research context. 'Impact' is now a critical element of any research funding proposal from public funds (e.g. the UK Research Councils) and research quality assessments that determine how much money is given to each individual university to support research. It is arguably the case that measurable or evidenced research 'impact' is more likely to arise from more integrated and synthetic research projects that incorporate and integrate a greater number and type of research 'elements', that is, methodologies/techniques, disciplines, commercial or other organisational partners (providing end-user perspectives).

The strength of geomorphology as an academic discipline lies in its fundamental importance to so many aspects of society, thus being well placed to succeed in the increasingly selective and output-driven research funding environment in the United Kingdom and many other countries. Multinational engineering companies have built up substantial and interdisciplinary geomorphology teams in recent years, and insurance companies as well as national governments continually seek improved evidence of probabilities of damaging natural hazards occurring requiring hydrological, ecological, geomorphological and socio-economic research. The latter example provides a practical application of geomorphological research to the issue of tectonic hazards, such as interpretations of new evidence for frequency, nature, scale and thus possible impacts of earthquakes, volcanic eruptions and tsunami in particular locations. It is perhaps unfortunate that insurers probably tend to use the higher end of any range of probabilities of occurrence (i.e. more likely), whereas policymakers may be keen to emphasise the lower end in order to defer having to commit to public spending on mitigation measures! However, as more different types of evidence are obtained and integrated, often from different disciplines and using different approaches and techniques, so the uncertainties are reduced, weights of evidence increased and overall credibility in any headline message is increased among the potential end users. John Thornes showed how geomorphology could integrate and structure information from other disciplinary areas and recognised the need for understanding complex systems in a non-reductionist way (e.g. Thornes 1985; Wainwright 2009). His collaboration with Antonio Gilman demonstrated the value of geomorphology to archaeology (Gilman and Thornes 1985), and there are many other examples of interdisciplinary research and commercial applications in ecology (Nortcliff and Thornes 1988), hydrology (Francis and Thornes 1990; Dykes and Thornes 2000), climate (Thornes and Alcántara-Ayala 1998) and society (Trimble and Thornes 1990; Thornes 2005).

Aims, purpose and structure of this book

The aim of this book is to demonstrate the lasting significance of the integrated monitoring and modelling philosophy of geomorphological research pioneered by John Thornes, by reporting recent and ongoing research and applied work that utilise this approach. This collection of work includes a wide range of types of research and applied studies undertaken using this integrated approach and, as such, serves to demonstrate the value and effectiveness of adopting such an investigative framework. The authors of all of these works are academics and practitioners who were either taught by John Thornes as postgraduate (and in one case undergraduate) students or who worked with him on one or more research projects, and their present colleagues and research partners. John's inspirational teaching and leadership is reflected in the enthusiasm with which the contributors agreed to write for this book, which should also serve as a lasting tribute to his academic career as a leading geomorphologist. The book is structured in two parts. The first is made up of studies inspired and informed by the philosophy outlined earlier, while the second reflects more directly on John's own contributions to the discipline.

Part 1 of the book is made up of chapters that vary in emphasis from data collection (monitoring) at one extreme to the application of models to policy development at the other. The first six chapters cover this range and, as such, broadly parallel the changing focus of John Thornes' research in Spain and, later, most of southern Europe. Romero Díaz and Ruíz Sinoga (Chapter 2) examine the measurement of soil erosion in Spain, starting with methods initiated by John Thornes. Through their examination of scale effects and other factors relating to the measurement and monitoring techniques used, they highlight the potential difficulties of obtaining data that can be used reliably to quantify soil loss and, thus, set up and indeed validate models of soil erosion for varying soil, slope and vegetation conditions in particular. Cerdà et al. (Chapter 3) report findings from a later stage of experimental fieldwork that examined the influence of shrubs on the hydrological and erosional conditions of Spanish hillslopes, demonstrating an effect identified and argued by John Thornes long before relevant monitoring was undertaken to provide data that could enable the effect to be modelled. Hooke and Mant (Chapter 4) further highlight the difficulties of parameterising models in their presentation of combined flood and vegetation change data for ephemeral channels in Spain. In this study, the integration of two themes – channel morphology and vegetation dynamics – appears to have greatly increased the apparent level of complexity inherent in the connectivity between these landscape components.

More emphasis on the value of modelling is provided by Wainwright (Chapter 5) who discusses conceptual frameworks for attempting to analyse the nature of the complexities of past land use and associated geomorphological change in the Mediterranean region. The key element here is the development of a non-linear modelling framework that integrates not only vegetation and erosion processes but also the evidence of patterns of human settlement, effects of agricultural practices and, often, later abandonment. In Chapter 6, Brandt and Geeson explain how the scientific findings of the desertification research relating to contemporary environmental and socio-economic pressures, that is, incorporating anthropogenic factors integrated with knowledge of the range of geomorphological and ecological processes, were made available to end users. This chapter demonstrates the importance of engaging with all types of end users from practitioners to managers, as well as other scientists, while undertaking the research and designing the outcomes of the research to be as user-friendly as possible across the board. Mulligan (Chapter 7) takes many of these ideas a further step forward by presenting the historical timeline of a web-based modelling framework that simulates the effects of particular policy decisions relating to management of sensitive and highly variable landscapes in the Mediterranean and beyond. With provenance in the early monitoring and modelling of Mediterranean desertification under John's supervision, this framework is now a sophisticated spatial policy support system in wide use at various levels of decision-making around the world.

Subsequent chapters present hydrological, geomorphological and environmental management studies undertaken in a variety of global contexts, reflecting the very wide range of John's interests and activities beyond his core focus on the Mediterranean region. His particular concern for water resources and water management in semi-arid environments and elsewhere, as well as natural hydrological processes and systems, provide a common theme for Chapters 8–10. In Chapter 8, Francis and Lowe examine the studies behind the preparation of a strategic integrated regional plan for sustainable development in the Rift Valley Lakes Basin of Ethiopia and in particular the assessment of environmental impacts of any natural resource exploitation. There is an emphasis on water resources throughout a programme of work that necessarily and explicitly followed an 'integrated philosophy'. Watts, on the other hand (Chapter 9), focuses on the modelling of water resource planning for the United Kingdom, highlighting both the modelling and management issues driving the approaches used and the application of the research findings. Marsik et al. (Chapter 10), concerned with changing river flows potentially reducing water supplies in Costa Rica, present research findings that attempt to explain the changing discharges in terms of catchment-wide land-use and/or climate change. They highlight the importance of combining multiple approaches in order to adequately investigate the problem.

The next three chapters focus on different types of geomorphological research. Afana and del Barrio (Chapter 11) present an adaptive model of channel network development that has been designed to facilitate the future integration of additional catchment properties to enhance the depiction of landscape change. The DEM framework provides the basis for parameterisation, in contrast to the work reported by Dewez and Stewart (Chapter 12) in which the DEM *is* the landform model. Here, the results of a semi-automated analytical procedure are interpreted with respect to the local tectonic context to explain the formation of a sequence of coastal terraces. In Chapter 13, Dykes and Alcántara-Ayala use slope stability models as part of an investigation of the role of land-use changes in the incidence of damaging landslides in Mexico. The context of land-use monitoring is reviewed, and the difficulties of utilising such land-use data in stability and hazard analyses are demonstrated.

Part 2 comprises a short collection of overviews of John's contribution to geomorphological research and the application of that research to real-world problems, rounded off with a short biography, written by some of his major contemporaries, colleagues and friends. The purpose of these chapters is to provide a scientific and historical context for (i) the wide range of related contemporary research in semi-arid regions and particularly in Mediterranean countries and (ii) the interests and scientific approaches utilised by students and colleagues of John that were strongly shaped by his influence.

We believe that John would have approved of the continuing sense of scientific rigour and exploration embodied in the studies presented here. That his influence continues on to present and future generations is a fundamental reflection of the significant advances that he made both directly in the discipline of geomorphology and more broadly in developing approaches to sustainable management of the environment.

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PART A

CHAPTER 2

Assessment of soil erosion through different experimental methods in the Region of Murcia (South-East Spain)

Asunción Romero Díaz[1] and José Damián Ruíz Sinoga[2]

[1] *Department of Geography, University of Murcia, Murcia, Spain*

[2] *Department of Geography, University of Málaga, Málaga, Spain*

Introduction

The Region of Murcia has been one of the pioneering Spanish regions in studying and assessing water erosion processes using experimental methods (García Ruiz 1999; Cerdà 2001; García Ruiz et al. 2001; Romero Díaz 2002; Solé Benet 2006; Añó Vidal et al. 2009). Studies on erosion plots started in the 1980s and were carried out almost simultaneously by two research groups. One of these research groups was coordinated by Professor López Bermúdez from the Geography Department at the University of Murcia (UMU), and the other was led by Juan Albaladejo, a researcher at the Centre for Soil Science and Applied Biology of the Segura (CEBAS)-Higher Council of Scientific Research (CSIC) who was in charge of assessing the Abanilla–Fortuna basin. Up to then, the existing values for erosion rates in the Region of Murcia had been calculated using the Fournier index (Fournier 1960) or models such as the USLE, which have been shown to overestimate erosion when compared to measured rates (Soto 1990).

This chapter presents erosion data obtained using several different techniques and methods originally initiated in the Region of Murcia by Professor John Thornes, with the aim of establishing, to the greatest extent possible, a comparison of their results. Needless to say, each method measures different processes at different scales, but they all contribute to the understanding of the causes of the wide range of values of erosion rates that are observed.

The study area: The Region of Murcia

Soil erosion is favoured in those environments where two important factors converge: rainfall erosivity and high soil erodibility. These two factors occur together in the Region of Murcia. From a climatic point of view, the Region of Murcia has a semi-arid climate, with low rainfall (300 mm a year on average) and high evapotranspiration. One of its most characteristic climatic traits is the high irregularity and variability of rainfall. Periods of long droughts are found together with heavy rainfall which, at certain times, can have catastrophic consequences due to flooding (Romero Díaz 2007). Forest-restoration policies have been, and still are, a priority in this region. On the other hand, it is important to mention the role of heavy

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rainfall periods (Albaladejo et al. 2006). Several studies based on experimental plots have suggested that a small number of heavy rainfall events have caused most of the soil loss in the Region of Murcia. López Bermúdez et al. (1986) showed in the Rambla de Gracia how 86% of soil loss was registered during three storms; Castillo et al. (1997), in a study which was also carried out on experimental plots in the Abanilla basin, pointed out that 80% of the total soil loss was caused by five storms in 5 years; and Martínez-Mena et al. (2001) illustrated how 70–80% of the total surface runoff and soil loss was caused by four extreme events in two experimental microcatchments in the northeast of the region.

The soil is poorly developed in the Region of Murcia, a fact that strongly affects its vulnerability to erosion. From a lithological point of view, there are numerous Neogene–Quaternary basins (Romero Díaz and López Bermúdez 2009) with soil parent materials dominated by marls, conglomerates and gypsums, all of which are particularly prone to erosion, forming gullies and badland landscapes (Figure 2.1). Due to the climatic conditions, the region has a sparse vegetation cover over a large part of its territory that provides only limited soil protection. Various studies can be found on the role of vegetation as a soil-protection factor. In the case of the Region of Murcia, the first works carried out, with the help of Professor John Thornes, were López Bermúdez et al. (1984, 1986), Francis et al. (1986), Fisher et al. (1987), Romero Díaz et al. (1988) and Francis and Thornes (1990). They were followed by Martínez Fernández et al. (1995), Romero Díaz et al. (1995), Castillo et al. (1997), López Bermúdez et al. (1998) and Gómez Plaza et al. (1998). In addition, Belmonte Serrato and Romero Díaz (1992, 1999) and Belmonte Serrato et al. (1999a, b) explicitly examined the role of vegetation in rainfall interception as part of this programme of research. Other studies showed how once the vegetation cover has been eradicated, its recovery is sometimes very slow and, on particular occasions, impossible to achieve (Barberá et al. 1997; Castillo et al. 1997; Albaladejo et al. 1998).

A third factor is human actions. Human beings have favoured the acceleration of certain erosion processes by using inadequate agricultural and farming practices and, more recently, abandoning crops that were formerly terraced (Sánchez Soriano et al. 2003; Lesschen et al. 2007; Romero Díaz et al. 2007a). Sometimes, crops are found on steep slopes where high soil losses have been reported, as in the case of the western area of Lorca and the northern area of Puerto Lumbreras (Ortiz Silla et al. 1999). Ploughing in the same direction as the slope is the usual practice in the region, but it also promotes erosion. This effect has been experimentally corroborated in the field at El Ardal, where a plot that was ploughed in this direction always registered the highest erosion rate (Romero Díaz et al. 1995).

Experimental sites in the Region of Murcia

The Department of Physical Geography at the UMU has investigated erosion processes at several experimental sites including (1) Rambla de Gracia, (2) El Ardal, (3) Los Guillermos and (4) El Minglanillo:

1 The first experimental site was set up in the Rambla de Gracia (in the Mula basin) in November 1983 with the participation of Professor John Thornes (Francis et al. 1986). It was a 60×50 m (3000 m^2) plot, placed on a hill with sparse vegetation cover. Ten Gerlach troughs were installed and distributed over the surface area. Six tanks of 972 l each were also placed at the base level of two small microcatchments within the area to collect the surface runoff. The site was eventually abandoned because of vandalism to the experimental equipment.
2 The experimental site of El Ardal was set up in 1989 and also benefitted from the presence of Professor Thornes. This area is located in the headwaters of the Mula basin, over a limestone substrate, with an average slope gradient of

Figure 2.1 Location of the Region of Murcia and erosional areas with gullies and badlands (dark grey scale) (MMA 2002).

20%, good vegetation cover with Mediterranean scrubland dominating the top part and a cereal field at the lower part (López Bermúdez et al. 1998). The cereal crop has now been replaced by an almond orchard. The experimental site houses a small micro-catchment of 2 ha where a flow-measuring flume was installed with a level sampler for assessing suspended sediments. Seventeen closed plots were located, 12 of 16 m^2 and 5 of 20 m^2, with different orientations, slope gradients, density of vegetation cover and land use (abandoned, in crop rotation, cultivated or using certain farming systems). Apart from measuring erosion and surface runoff, other experiments have been carried out on this site to assess fertility loss (Alias et al. 1997) or the role of vegetation, particularly evolution of the vegetation cover, biomass and leaf production (Martínez Fernández et al. 1993, 1995) and interception studies (Belmonte Serrato and Romero Díaz 1999). The erosion plots in El Ardal are no longer functional since they showed symptoms of soil exhaustion

(Belmonte Serrato et al. 2002). In the MEDALUS project, led by Professor Thornes in its first, second and third phases (1991–1998: see Chapter 16 by Kirkby et al., this volume), El Ardal was one of the study fields selected, and the data it provided would serve to test erosion models (Kirkby et al. 2002). Later on, the Guadalentín basin became the main experimental site, with numerous researchers from different countries working on it (Geeson et al. 2002).

3 The experimental site in Los Guillermos was set up in 1991, in the middle of the Rambla Salada, to the south of the Mula basin. The selected area is a badland landscape in a Neogene–Quaternary sedimentary basin formed by marls, conglomerates and sands (López Bermúdez et al. 1992). In the gully headcut, three stations for flow measurement with flumes were installed with different orientations in three microcatchments of 120 500 and 3 000 m^2; five erosion plots of 16 m^2 with different slope gradients, vegetation cover and stony surfaces were also established. Several studies on soil micromorphology (Conesa García et al. 1994, 1996) and numerous rainfall simulations (Fernández Gambín et al. 1995, 1996) were carried out on this site. However, the great quantity of sediments deposited after rainfall events rendered the measuring systems useless and continuous vandalism also caused the site to be abandoned.

4 In 1995, the experimental site of El Minglanillo was set up in the basin of the Rambla Salada on a Quaternary glacis over Tertiary marly materials (López Bermúdez et al. 2000). Three plots of 20 m^2 were installed on the bare soil of an abandoned crop, on harvested soil and under natural vegetation. Data obtained from these plots on marls were of great interest in order to compare them with plots on limestone (Romero Díaz and Belmonte Serrato 2002). Following these studies, numerous experiments have taken place in other areas of the region, especially in the basin of the Quípar river and in the Guadalentín valley (Figure 2.2).

Studies of erosion have been carried out at experimental stations of the CEBAS-CSIC:

5 The first station was set up in Abanilla in 1988. It was formed by two closed plots of 87 m^2 each, and the aim was to study the soil-degradation processes induced by the impoverishment of vegetation cover and the validation of physically based soil erosion models (Albaladejo and Stocking 1989).

6 In Santomera, two plots of 15 × 5 m were installed in 1989 (Castillo et al. 1997; Albaladejo et al. 1998; Martínez-Mena et al. 2002), one maintaining the original vegetation (open scrubland with pines) and another eradicating the vegetation cover in order to check the effects on erosion, surface runoff and soil properties.

7 In 1989, another experimental site with five plots was installed in Abanilla. The aim was to study the effects of incorporating different quantities of organic urban solid refuse (USR) into underdeveloped and degraded soils, formed from marls affected by intense erosion processes. One of the plots was left as a control, and different quantities of USR were incorporated into the other four (Albaladejo et al. 2000).

8 In 1991, the experimental microcatchments of Abanilla with 759 m^2 and Color with 328 m^2 were installed in the Chícamo river basin, on marls and Quaternary deposits, with dispersed small-sized bushes (*Stipa tenacissima* and *Rosmarinus officinalis*) and soils with low permeability and organic matter (Martínez-Mena et al. 2001).

9 In 1997, another experimental site with three basins was installed to the south of the Sierra del Picarcho (Venta del Olivo), with the aim of studying the factors which control surface runoff processes at different working scales, analysing the variability of these factors and developing and validating hydrological simulation models adapted to these environments. Two of the basins, with surface areas of 7.9

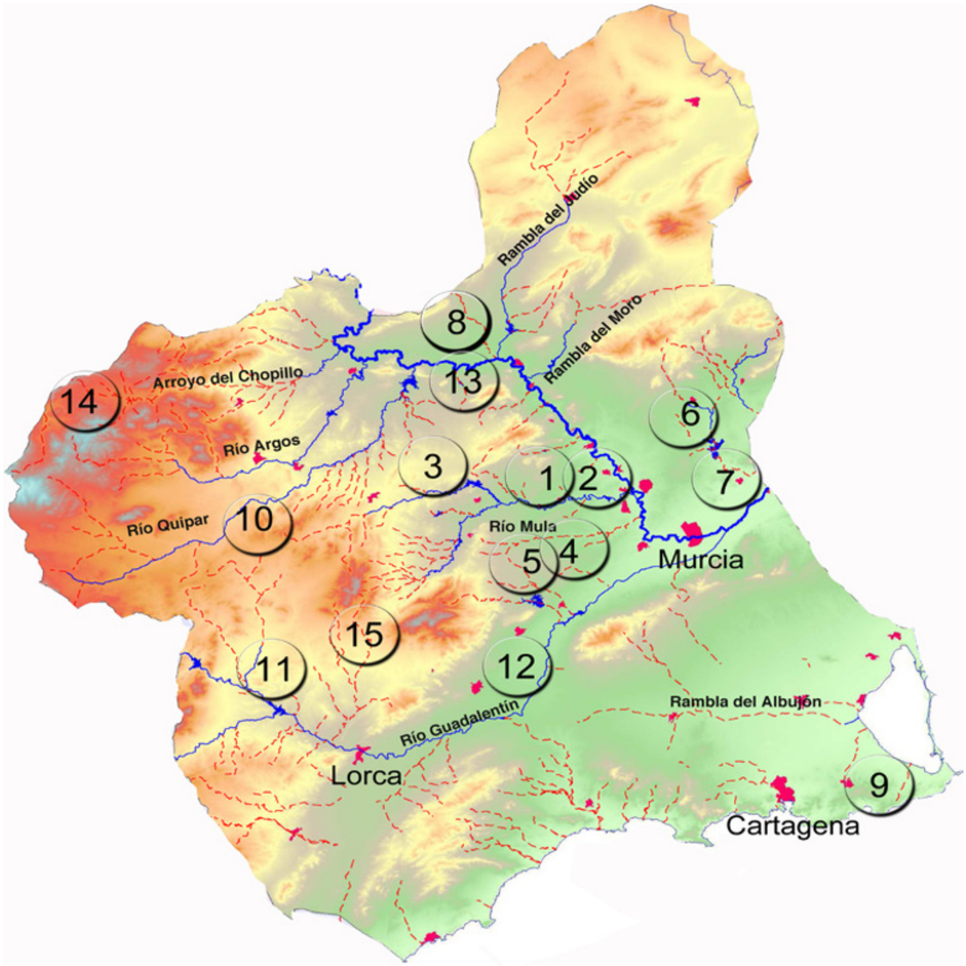

Figure 2.2 Main areas of the Region of Murcia where erosion processes have been studied. 1. Rambla de Gracia; 2. Rambla Honda; 3. El Ardal; 4. Los Guillermos; 5. El Minglanillo; 6. Abanilla; 7. Santomera; 8 Sierra del Picarcho; 9. Sierra de Cartagena-La Unión; 10. Quipar river basin; 11. Head of the Giadalentín basin; 12. Guadalentín river basin; 13. Cárcavo basin; 15. Cañada Hermosa.

and 6.4 ha, were located in a field that burned in 1994 with *S. tenacissima* in regeneration; the third one, with a larger surface area (24.3 ha), was not affected by burning and was dominated by vegetation cover with *S. tenacissima* and clear pine forest of *Pinus halepensis*. In each of the basins, a sediment sampler was installed with a battery of five bottles at different heights. Six closed plots of 30 m^2 (10 × 3 m) were set up in the basins, two on *S. tenacissima* in a burned area, two on *S. tenacissima* in an unburned and well-developed area and two in a pine forest. Nine microplots of 0.24 m^2 were also set up for rainfall simulation experiments in areas with different soil and vegetation characteristics. The period of activity went from 1997 to 2003 (Castillo et al. 2003).

In the case of the studies carried out by the Department of Physical Geography, experimental work on soil erosion began with the arrival of Professor Thornes. He participated in setting up the first erosion plots in the Mula basin, making the first rainfall simulations, studying the role of scrubland in protecting soil and obtaining the first data on soil erosion. From there onwards, a whole series of projects was run among which the different phases of the MEDALUS programme deserve a special mention. In all of them, Professor Thornes took a very active part. His influence on this work was decisive; he participated in obtaining the first experimental data on erosion, co-authored the first publications and contributed to the enrichment of the work by providing useful methodological training and valuable scientific rigour. This chapter presents the data obtained from the many studies outlined earlier, using different techniques and methods, with the aim of comparing and evaluating the results.

Soil erosion experimental methods and results obtained in the Region of Murcia

Experiments to quantify soil erosion in the Region of Murcia have been carried out using different study methods at different scales and on different lithologies (marls, marls and gypsums, limestones, sandstones, conglomerates, schists and phyllites) and land uses (fields with crops, semi-natural vegetation, forests and abandoned fields). The methods used depend on the scale of study: (i) on a millimetric scale, erosion pins and microtopographic profiles (Sancho et al. 1991) are normally used; (ii) on a hillslope scale, the most commonly used methods are erosion plots (López Bermúdez et al. 1993), rainfall simulations (Calvo et al. 1988; Cerdà 1999), surveying and geomorphological transects (Ortigosa Izquierdo 1991; Ruiz Flaño 1993; Romero Díaz and Belmonte Serrato 2008); and (iii) on a basin scale, flow measurement with flumes and bathymetry of reservoirs are used (Avendaño and Cobo 1997; García-Ruiz and Gallart 1997). More recently, sediment retained behind check dams (Romero Díaz et al. 2007b) has also been measured.

Erosion pins

This is a very simple and widespread method used in Spain, adopted from the first works by Scoging (1982), especially in those areas where erosion rates were assumed to be high. This method generally lacks precision and tends to provide higher values than those obtained by other methods such as erosion plots. This comparison has been discussed by Haigh (1981), Sirvent et al. (1997), Benito et al. (1992), Cerdà (2001) and Wainwright and Thornes (2004).

In the case of the Region of Murcia, erosion pins have been used for different purposes, for example, (i) calculating the volumes of eroded material in the headcut of gullies (Francis 1985) and the dynamics of piping processes (Romero Díaz et al. 2009); (ii) estimating the erosion of mining waste in the Sierra de Cartagena-La Unión (Moreno Brotons 2007); (iii) assessing the sediments retained by check dams after each period of rainfall (Romero Díaz et al. 2007c); and (iv) checking the role of different vegetation species in retaining sediments on hillslopes. This last aspect was studied using different species at the beginning of the 1980s, with Professor Thornes in the Rambla de Gracia. This work provided evidence that showed how *S. tenacissima* was, out of all the studied species (*Stipa*, *Rosmarinus* and *Thymus*), the one which retained most sediments. For this reason, *S. tenacissima* could be considered as one of the potentially most effective species for stabilising hillslopes and reducing erosion. Unfortunately, the results of these observations were not published. Sánchez (1995) reached the same conclusion in his doctoral dissertation on the architecture and dynamics of *S. tenacissima* plants.

During 3 years of sediment research (2003–2005) following the placement of numerous erosion pins upstream from 51 check dams within the Quípar river basin (Romero Díaz et al. 2007b), the erosion rate from the 3-year period of sediment research and from the total

Table 2.1 Erosion rates obtained by erosion pins in check dams, Quípar river basin.

Sub-basin	Number of controlled check dams	Rate from the 3-year period ($t\,ha^{-1}\,year^{-1}$)	Rate from the total period ($t\,ha^{-1}\,year^{-1}$)
1, 2, 3	11	0.11	0.71
4	11	0.90	3.39
5	5	1.49	2.64
6	6	2.41	5.29
	Total = 51	Mean = 1.37	Mean = 3.95

From Romero Díaz et al. (2007b).

period of the useful life of the check dams was calculated (Table 2.1). The erosion rate from the 3-year period was lower than that from the total period because the rainfall registered during the 3-year period was not very high and did not, therefore, generate very active erosion.

Several measurements have been carried out using microtopographic profiles, but none with significant results. In the experimental field of El Minglanillo, the evolution of a network of rills in an almond plot of 34 × 100 m (López Bermúdez et al. 2000) started to be assessed, but unfortunately, the owner of the farm ploughed the field, putting an end to the experimental work.

Erosion plots

Erosion/runoff plots are the most widely used methods to quantify the amount of soil exported, primarily by interrill runoff. The typology of the plots used is very varied depending on the objectives, the area of study or the economic resources available (López Bermúdez et al. 1993). There are two basic types of plots: (i) open and (ii) closed. Most of the data obtained in Murcia came from closed plots.

Open plots

In open plots, collectors similar to those devised by Gerlach (1967) are installed to measure the transfer of sediments along a hillside. It has the advantage that measurements can be carried out for a long time, since water flow upstream is not interrupted. On the other hand, on closed plots, sediments are depleted and must be abandoned after some time (Belmonte Serrato et al. 2002). However, open plots also have some disadvantages, such as problems with the demarcation of their slope area and the overflowing of the collectors during intense rainfall.

The open plot type of collector was installed, with Professor Thornes' collaboration, in the experimental area of the Rambla de Gracia (López Bermúdez et al. 1986). The collectors were installed in 1984 on a hillside with low-density scrubland, and the soil loss data obtained during a period of 2 years (1985–1986) ranged from 1.8 to 3.2 $t\,ha^{-1}\,year^{-1}$ (Francis 1986; Romero Díaz et al. 1988). These values correspond with those reported by other authors who have used the same method in other parts of Spain.

From 1996 to 1999, Cammeraat (2002, 2004) carried out studies with open plots in Cañada Hermosa (at the headwaters of Guadalentín basin), obtaining very low erosion values in scrublands and areas reforested with pine on limestones (0.08 $t\,ha^{-1}$ on average per event). In contrast, in marl and valley bottom areas, his measured rates exceeded 30 $t\,ha^{-1}$.

Closed plots

Closed plots also have numerous disadvantages but are, nevertheless, a widely used method and can provide very interesting data (López Bermúdez et al. 1993). In Murcia, the first erosion data from closed plots were provided by Francis (1986). They came from plots of 3 × 1 m installed in crops abandoned for 1, 2, 5 and 20 years in the Rambla Honda. The rates obtained ranged from 0.8 to 5.3 t ha^{-1} $year^{-1}$. Soil loss was higher in the fields abandoned for 20 years.

From 1989 to 1999, the experiments carried out in El Ardal (López Bermúdez et al. 1996) on a limestone substrate with good vegetation cover, and under different weather conditions, obtained low erosion rates. From 1989 to 1997, the average erosion rate was less than 1 t ha^{-1} $year^{-1}$ (Romero Díaz et al. 1998). Nevertheless, when different soil uses were analysed, significant differences appear. The objective of this experimental site was not to obtain high erosion rates, but rather observe the existing variations of different parameters (soil uses, orientation and hillslope). Thus, plots covered by scrubland provided the lowest erosion rates (0.06–0.22 t ha^{-1} $year^{-1}$), followed by those where bush vegetation had been cut, but still kept some vegetation (0.43–0.94 t ha^{-1} $year^{-1}$), and those which were abandoned (0.01–0.50 t ha^{-1} $year^{-1}$). Cultivated and ploughed plots provided the highest rates (0.78–1.20 t ha^{-1} $year^{-1}$). Those plots with wheat and barley crops registered high erosion rates, coinciding with periods of intense rainfall at the time when soil was least protected (from the middle of summer to winter). The highest rates were found in plots ploughed up and down (5.92 t ha^{-1} $year^{-1}$) (see Figure 2.2). The experiments in El Ardal and similar ones carried out in Is Olias (Italy) and Spata (Greece) demonstrated the importance of land use and the consequences that changes in land use can have for increasing soil degradation and erosion (Romero Díaz et al. 1999).

The erosion rates obtained on marls in El Minglanillo were much higher. For the 1997–1999 period, the rates were 7.47 t ha^{-1} $year^{-1}$ on crops, compared with 0.80 t ha^{-1} $year^{-1}$ on scrubland and 1.12 t ha^{-1} $year^{-1}$ on abandoned fields. The comparison carried out for the same rainfall events and the same period of study by Romero Díaz and Belmonte Serrato (2002) in the two experimental sites of El Ardal and Minglanillo illustrated the influence of lithology. For the same plots, López Bermúdez et al. (2000) provided values for 5 years (1996–2000) which ranged from 6 to 15 t ha^{-1} $year^{-1}$ on crops, 0.7–1.4 t ha^{-1} $year^{-1}$ on scrubland and 0.14–2 t ha^{-1} $year^{-1}$ on abandoned fields.

The results obtained in the experiments carried out by CEBAS on the plots installed in Santomera showed the contrast between those areas covered by vegetation and those lacking it (Figure 2.3). After a follow-up period of 55 months, one of the plots deprived of vegetation

(a)

(b)

Figure 2.3 Experimental plots in Santomera: (a) adjacent plots with and without vegetation (CEBAS) and (b) an unvegetated plot ploughed up and down a hillslope after a rainfall period in El Ardal (UMU).

displayed a noteworthy loss of organic matter and a prominent decrease in the percentage of stable aggregates. Soil loss increased by 127% in the disturbed plot, which was attributed to a progressive deterioration in the physical properties of the soil. No symptom of natural recovery of the plot without vegetation was observed. Rather, the tendency in soil behaviour was towards a state of degradation (Castillo et al. 1997; Albaladejo et al. 1998). By analysing also the distribution of sediment particles, Martínez-Mena et al. (1999) observed how the vegetation cover reduced the eroding power of rain by around 50% and also reduced runoff by around 75%, especially during high-intensity rainfalls.

From October 1988 to September 1993, experiments carried out with USR in the Abanilla basin using different rates of addition (6.5, 13.0, 19.5 and 26.0 $kg\,m^{-2}$) to the soil confirmed a notable decrease in runoff and soil losses. Physical properties of soil were improved, increasing the productivity and, therefore, protecting the soil against erosion. The control plot displayed values that were much higher than those in treated plots, independently of the addition rates of USR. A rate of around 10 $kg\,m^{-2}$ could be optimal for control of runoff and erosion; higher rates were not necessary and could increase the risk of soil pollution (Albaladejo et al. 2000).

Research carried out for 4 years on closed plots of 30 m^2 in the Sierra del Picarcho (Venta del Olivo) in areas of burned scrubland and unburned scrubland and pine forests showed higher rates of sediment production in the burned scrubland (0.54 $t\,ha^{-1}\,year^{-1}$) when compared with the unburned one (0.03 $t\,ha^{-1}\,year^{-1}$). In general, the erosion rates were low due to the existing vegetation cover, and the experiments demonstrated the role of high-intensity rainfall in generating runoff and erosion (Boix-Fayos et al. 2007). Notable differences were reported between burned and unburned areas. The runoff ratio was much higher (80–90%) in burned areas, which further demonstrated the important role of vegetation as a protecting factor.

On different lithologies (marls, conglomerates and schists) of the Guadalentín basin, Romero Díaz and Belmonte Serrato (2008) installed closed plots of 10×2 m during the years 2005–2006 in places with dispersed natural scrubland and near reforested areas. The aim was to compare erosion rates between forested and non-reforested areas. The rates obtained were very low on all the plots, being higher on marls (1.86 $t\,ha^{-1}\,year^{-1}$), followed by schists (0.11 $t\,ha^{-1}\,year^{-1}$) and lastly conglomerates (0.06 $t\,ha^{-1}\,year^{-1}$). This work illustrated differences between lithologies and the protecting role of shrubland cover, even when that cover is scarce and small in size.

Experimental catchments

Studies made on a catchment scale in the Region of Murcia are not so numerous. The first studies were carried out in small microcatchments: (i) in the Rambla de Gracia (Mula basin) on an area of 3000 m^2 from 1984 to 1986 and (ii) in the Chícamo river basin in two small microcatchments of 328 and 759 m^2 (Color and Abanilla) from 1990 to 1993. In the Rambla de Gracia, the erosion rates ranged from 0.08 to 2.36 $t\,ha^{-1}\,year^{-1}$ (Romero Díaz et al. 1988), and in the second site, the rates ranged from 0.85 to 2.99 $t\,ha^{-1}\,year^{-1}$ (Martínez-Mena et al. 2001).

From 1997 to 2003, there were experiments in catchments of greater surface areas (6.4, 7.9 and 24.3 ha) which took place in the Sierra del Picarcho. The erosion rates were very low compared with those in the microcatchments with mean values ranging between 0.034, 0.011 and 0.015 $t\,ha^{-1}\,year^{-1}$ (Boix-Fayos et al. 2006). Other experiments have been carried out in different parts of the Guadalentín basin by Hooke and Mant (2000), Oostwoud Wijdenes et al. (2000) and Cammeraat (2002, 2004).

Despite the difficulties involved in the hydrological study of experimental catchments in semi-arid areas due to low rainfall, their importance has been strongly demonstrated. However, establishing the rates for erosion or sediment export is not as important (García-Ruíz and López Bermúdez 2009) as defining the factors that control runoff and erosion. Understanding the spatio-temporal variations that take place in the basins in order to predict their hydrological response is also an important factor to take into account.

Rainfall simulations

Rainfall simulations have normally been used to estimate the infiltration capacity of soils, compare the hydrological responses of different microenvironments and analyse the specific role that surface characteristics (Albaladejo et al. 2006). Sometimes, they are also used to estimate erosion rates. Nevertheless, these data are very difficult to extrapolate due to the small surface areas where simulations are carried out, the great variability in rainfall intensity and quantity and the different types of simulators (Cerdà 1999). Despite these, the values obtained using simulations allow us to compare surface areas, seasons and soil uses and identify the areas more prone to producing large quantities of sediments.

There are different types and different sizes of simulators (Calvo et al. 1988; Cerdà 1999). In the Region of Murcia, simulators of 0.25, 2 and 20 m^2 have been used. One of the first rainfall simulation experiments in Spain was done in Murcia in the early 1980s under the initiative of Professor Thornes (Francis 1986; Francis and Thornes 1990). In the 72 experiments carried out by Francis (1986) in the Mula basin, the rates obtained on soils with different periods of abandonment and in different hydrological conditions (wet and dry) were relatively high due to the heavy simulated rainfall that was applied. The average erosion rate on dry soil decreased from 7.7 t ha^{-1} $year^{-1}$ in recently abandoned land to 1.6 t ha^{-1} $year^{-1}$ in soil abandoned 20 years before. In experiments performed on wet soils, erosion rates were slightly higher.

Calvo et al. (1991) performed different simulations in the badlands located to the south and south-east of the Iberian Peninsula. One of the selected areas was the badlands formed in the Plio-Quaternary near Sucina (Campo de Cartagena).

In the Guadalentín basin, the simulations run by Cerdà (1997) on different soil types showed that cultivated soils did not generate runoff due to their high macroporosity and that soils abandoned for 3 years generated between 0.2 and 6.4 t ha^{-1} $year^{-1}$. Rates decreased when the abandonment period was longer or when there was more vegetation cover. Depending on the type of soil and the level of rainfall, abandonment may increase or reduce the erosion process.

In the Abanilla basin, Martínez-Mena et al. (2001) obtained higher averages on Miocene marls than on Keuper marl outcrops using a similar simulator (0.24 m^2) to those employed by the aforementioned authors and under dispersed scrubland. In Fuente Librilla, Martínez-Mena et al. (2002) used a larger simulator (2 m^2) in lemon tree groves and obtained higher soil losses than on Tertiary marls when compared to limestone colluvia.

The studies performed in El Ardal with a large simulator (2 × 10 m) (Figure 2.4) must be highlighted. In this case, very little runoff was registered during the simulations, which may be due to the lithological characteristics and the existing vegetation cover. Using simulated rainfall in El Ardal, Bergkamp et al. (1996) demonstrated that the infiltration pattern was related to vegetation organisation in patches separated by bare soil. On the bare soil, surface runoff and ponding are favoured, whereas vegetation favoured infiltration.

Bathymetry of reservoirs

The use of bathymetry in reservoirs is another method of estimating erosion rates. This method has also been used in the Segura basin (in one of the areas within the Region of Murcia). It is laborious as it requires the combined use of photogrammetry, bathymetric and sedimentological techniques, as well as the calculation of parameters such as the grading, density and composition of the sediment and the exploitation regime and retention capacity of the reservoir. The calculation of sediments retained by a dam provides data on 'specific degradation',