Introduction

Hooke, J.; Barberá, G.; Cammeraat, L.H.; Castillo, V.; Poesen, J.; Torri, D.; van Wesemael, B.

DOI
10.1007/978-3-319-44451-2_1

Publication date
2017

Document Version
Final published version

Published in
Combating Desertification and Land Degradation

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Chapter 1
Introduction

Janet Hooke, Gonzalo Barberá, L.H. Cammeraat, Victor Castillo, Jean Poesen, Dino Torri, and Bas van Wesemael

Abstract This book explains the methods and results of a major research project, RECONDES, that was undertaken to develop strategies of effective use of vegetation to combat desertification and land degradation by water. The research approach combined understanding of the processes of erosion and land degradation with identification of suitable and effective plants and types of vegetation that could be used to decrease the intensity of soil erosion. The project uses the relatively new concept of physical connectivity of water and sediment in the landscape. The premise of the approach is that sediment connectivity can be reduced through the development of vegetation in the flow pathways, and that this approach is more sustainable than use of physical structures. It required research into the locations and characteristics of these pathways and into properties of suitable plants and species at a range of scales and land units. These components are combined to produce a spatial

J. Hooke (✉)
Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Roxby Building, L69 7ZT Liverpool, UK
e-mail: janet.hooke@liverpool.ac.uk

G. Barberá • V. Castillo
Centro de Edafologia y Biologia Aplicada del Segura (CEBAS), Department of Soil and Water Conservation, Campus Universitario de Espinardo, PO Box 164, 30100 Murcia, Spain

L.H. Cammeraat
Instituut voor Biodiversiteit en Ecosysteem Dynamica (IBED) Earth Surface Science, Universiteit van Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

J. Poesen
Division of Geography and Tourism, Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium

D. Torri
Consiglio Nazionale Della Ricerche – Istituto di Ricerca per la Protezione Idrogeologica (CNR-IRPI), Via Madonna Alta 126, Perugia, Italy

B. van Wesemael
Earth and Life Institute, Université catholique de Louvain (UCL), Place Louis Pasteur 3, 1348 Louvain-la-Neuve, Belgium

J. Hooke, P. Sandercock, *Combating Desertification and Land Degradation*, SpringerBriefs in Environmental Science, DOI 10.1007/978-3-319-44451-2_1

strategy of use of suitable plants at the most strategic points in the landscape, designed for restoration or mitigation of land degradation. Additional benefits of use of vegetation as a strategy of sustainable management are outlined. The methods and restoration strategy were developed in relation to the dryland environments of the Mediterranean region of southern Europe, involving field measurements, monitoring and modelling in the study area in Southeast Spain, the driest and most vulnerable region in Europe to desertification.

Keywords Research methods • Sustainable land management • Landscape approach • Vegetation restoration • Soil erosion control • Catchment monitoring • Landscape connectivity

1.1 Context and Problem

Desertification and land degradation are major problems worldwide, with semi-arid and sub-humid lands particularly vulnerable. The extent of the areas affected and the severity of the problem are predicted to increase in the future under most land use and climate change scenarios (Lesschen et al. 2007; Safriel and Adeel 2005; Zollo et al. 2015). It is therefore an urgent and serious challenge to design and implement effective strategies and methods to combat desertification and land degradation.

Desertification is taken to mean the process of becoming desert-like (it therefore does not include the major arid land deserts that are 'naturally' and have long been deserts). In many regions the main processes of land degradation involve erosion by water. Elsewhere, especially in areas adjacent to sandy deserts such as in China, the major soil erosion processes are by wind, and deposition takes place as sand dunes, which may move and encroach on productive areas. In the processes produced by flowing water, major amounts of topsoil removal occur, leading to decreased soil quality, nutrient loss and reduced infiltration. These in turn produce a positive feedback by increasing runoff and hence further accelerating soil erosion. The soil material is transported down through the catchment, where it silts up reservoirs, or causes muddy flows during flooding. Overall, severe soil erosion and gullying of land result in loss of agricultural productivity, thus increasing poverty, migration and other social problems (Millenium Ecosystem Assessment 2005). Land degradation through these processes produces many negative 'on-site' and 'off-site' effects, especially during intense seasonal rainfall events.

It has long been recognised that the main way to combat desertification/land degradation is by increasing or at least maintaining vegetation cover (Millenium Ecosystem Assessment 2005). Conventional solutions for mitigating desertification include reforestation of large areas and the construction of check dams, both of which have long been used in some regions but which are costly. They also have detrimental effects and may not be that effective (Boix-Fayos et al. 2007; Boix-Fayos et al. 2008; Brown 1944). Soil conservation practices have also long been advocated and a wealth of literature exists on soil conservation techniques such as terracing, contour ploughing, use of grass strips, soil treatments and tillage strategies (Morgan 2005).

The purpose of this publication is to report a major research project that was undertaken to develop strategies of more effective use of vegetation to combat desertification and land degradation by water (RECONDES, http://www.port.ac.uk/research/recondes/). It demonstrates the approaches, methods and results in order to exemplify their potential wider application in other environments and in practical schemes. The approach was developed in relation to the Mediterranean environment but it has much wider potential applicability to dryland and vulnerable areas. Major problems with present approaches to mitigation or restoration in drylands are that either they are a blanket approach, as in afforestation covering whole hillsides or catchments, or piecemeal as in use of particular structures, or only work in the short-term, as with check dams. Some traditional and ancient practices are effective, for example agricultural terracing, but some of these are falling into disuse. The need was therefore to develop strategies that combine understanding of the processes of erosion and land degradation with identification of plants and types of vegetation that could be used to decrease the intensity of these processes. A major premise of the project is that much of the erosion and soil removal and its subsequent deposition occurs in limited pathways within the landscape and therefore these should be targeted. If vegetation is placed in these pathways then it can reduce erosion and transmission of effects but does not occupy all the land, so agricultural land can remain productive. The project uses the relatively new concept of understanding physical connectivity of water and sediment in the landscape. It required research into the locations and characteristics of these pathways and into properties of suitable plants and species. Another major premise of the project was that only indigenous species should be used in these strategies, because of problems caused by exotic species introduced to areas (see D'Antonio and Meyerson 2002, and Rodríguez 2006 for a review of the pros and cons and controversies about the use of exotic species in restoration).

In semi-arid areas, including the driest parts of Mediterranean Europe, erosion has still been detected in reforested areas as a result of a combination of poor tree growth, low ground cover and the terrace structures created for the forestry (Castillo et al. 2001). Check dams tend to provide only short-term solutions because they fill up very quickly in such environments (Cammeraat 2004; Lesschen et al. 2008a), and they are often breached, even by quite moderate storms (Borselli et al. 2006; Castillo et al. 2007; Hooke and Mant 2001, 2002; Poesen and Hooke 1997). Soil erosion on agricultural lands is the major problem (Cerdà et al. 2009) but modern land practice may also increase erosion risk by opening up long slopes and leaving land bare for periods (Borselli et al. 2006). These problems are likely to be exacerbated in many dryland and sub-humid areas in the future because of global climate change (IPCC 2007). A whole-landscape approach has been promoted in Belgium (AMINAL 2002; Evrard et al. 2007) but no attempt had been made, to our knowledge in 2004, to develop this approach in a Mediterranean environment, with its particular plants and cultural landscape features, notably agricultural terracing. Some knowledge on aspects of Mediterranean vegetation and plants existed at the time of the initiation of this project (Hooke 2007b) but detailed work on plant properties, growth requirements and response to processes was limited (Sandercock et al. 2007). Some work was ongoing into the use of plants for revegetating road cuttings in the region (Bochet et al. 2007; Tormo et al. 2007), since these are also major problem zones (Cerdà 2007), and for slope stabilisation (e.g. Mattia et al. 2005). Research on restoration of gullied and degraded areas includes experimental plantings in the Mediterranean Alps (Burylo et al. 2007) and much work is ongoing into other techniques to be applied in the Mediterranean region (e.g. García-Orenes et al. 2009; Giménez Morera et al. 2010). The present state of knowledge on soil erosion in the Mediterranean region is reviewed in Cerdà et al. (2010). Research on these various aspects is accelerating.

1.2 Processes and Connectivity Concept

Most of the soil erosion and land degradation in the Mediterranean region occurs by the movement of surface material downslope via water flow transport in rills, gullies and soil tunnels and micropipes. Erosion is greatest where flow velocities or shear stresses are highest, combined with low resistance of the top soil or surface, i.e. on steep gradient areas, and where runoff generation is greatest, notably bare surfaces. These are erosion hotspots. Erosion is much reduced where the vegetation cover is >30 % (Thornes and Brandt 1993). Once gullies or piping develop then these can be propagated rapidly up and downslope.

Conventional analyses relate erosion rates or sediment yield directly to catchment characteristics through statistical analysis or are derived from plot scale studies. More recently, the concept of connectivity has been applied to understand sediment flux in catchments, as well as to hydrological analysis (Bracken and Croke 2007; Reaney et al. 2007). Although this approach was developed in Australia (Brierley and Fryirs 1998; Brierley and Stankoviansky 2002; Fryirs and Brierley 2000; Fryirs et al. 2007b), it has been tested in Spain and Luxembourg (Cammeraat 2002; Imeson and Prinsen 2004), and in relation to coarse sediment connectivity in stream channels (Hooke 2003). Connectivity is defined in this context as “the physical linkage of water or sediment flux within the landscape and the potential for a particle to move through the system” (Hooke 2003). The importance of connectivity at local and hillslope scale, particularly the effects of vegetation patchiness in Mediterranean and semi-arid landscapes, was long ago recognised (e.g. Cammeraat and Imeson 1999; Cerdà 1997; Puigdefabregas et al. 1999) and such ideas are being used in practical management in Australia, following the important work of Ludwig and Tongway (2000) Ludwig et al. (2002) and Tongway et al. (2003). The catchment scale research on connectivity (e.g. Fryirs et al. 2007a; Quiñonero-Rubio et al. 2013) has demonstrated that major areas of storage can occur within the landscape, reducing the transmission of the sediment load downstream. It focuses on the major patterns of sediment removal some of which are missed by plot scale studies. It identifies pathways and 'hotspots' of erosion. The concept of connectivity was a major tenet of the RECONDES project and resulted in various methodological developments and methods of mapping, constituting a rich and varied series of contributions to the literature on the topic (Borselli et al. 2008; Lesschen et al. 2008a; Lesschen et al. 2008b; Lesschen et al. 2009; Marchamalo et al. 2016; Meerkerk et al. 2009; Sandercock and Hooke 2011; Vigiak et al. 2012).

1.3 Benefits of Use of Vegetation

Vegetation has several effects which are advantageous in reducing surface runoff of water (and therefore also making it more available to plants by infiltration into the soil) and reducing movement of soil and nutrients (Table 1.1). The advantages of using vegetation in a spatially strategic approach mean that it should be more sustainable and efficient than conventional approaches. With use of suitable plants then they should be self-sustaining. The major advantage of the spatially strategic approach, that only places vegetation in particular locations such as field boundaries, is that it is does not take up large areas of productive land and the budget for restoration may be much reduced to obtain an optimal or near optimal erosion reduction. This approach also increases spatial connectivity for wildlife, contributing to biodiversity conservation. Furthermore, in the longer-term this favours the formation of a soil biota, mainly fungi and michorrizae, whose interaction with plants produces soil organic matter (Rillig et al. 2015). Soil amelioration also improves ecosystem resilience, which is of outstanding importance due to ongoing

Table 1.1 Beneficial effects of vegetation in soil erosion and land degradation reduction

Feature	Effect(s)
Vegetation canopy	Protects the soil surface from the impact of rain drops, and direct solar radiation; both benefit biological activity and soil and aggregate formation processes
Vegetation structure (Stems & leaves)	Increases rugosity (roughness) and so lowers flow velocities and sediment transport; this will increase sedimentation
Root length density	Increases soil cohesion and hence resistance to erosion
Root-soil interface	Increased root length density increases porosity and macro-porosity thus promoting infiltration so increasing water availability to plants locally and decreasing flow downstream, ultimately helping reduce flood risk; interaction with soil biota favours soil aggregate stability, improving soil pore system stability and decreasing soil crust formation
Soil quality	Increases organic matter, texture, nutrient, water retention and microbiological activity
Carbon sequestration	More generally, sequesters carbon so mitigating greenhouse gas emissions and thus global warming impacts

climate evolution. Furthermore, favourable soil physical properties are maintained or improve under developing or permanent vegetation, enhancing soil porosity and infiltration. The approach developed and advocated in this project and publication is therefore a win-win situation.

1.4 Approach

The premise of the approach developed here is that sediment connectivity can be reduced through the development of vegetation in the flow pathways, and that this approach is more sustainable than use of physical structures (Sandercock and Hooke 2006). The approach requires the combination of understanding of the physical processes, particularly the connectivity pathways, and a knowledge of the suitability and effectiveness of plants to reduce erosion. These components are combined to produce a spatial strategy of use of suitable plants at the most strategic points in the landscape, designed for restoration or mitigation of land degradation in the dryland environments of the Mediterranean region of southern Europe. The steps in application of this approach are shown in Fig. 1.1. This strategy is designed (a) for application in areas which are prone to soil erosion by water, where vegetation is sparse, and primarily with agricultural land use, and (b) to 'work with nature' using indigenous and local plant species. The Mediterranean areas have a long tradition of agriculture where agricultural terraces have been built on steep slopes that are highly vulnerable to land degradation, especially where on soft bedrock such as marl. The use of local native species means that they are adapted to the local environmental conditions, and avoids problems of introducing exotic species. The general characteristics of suitable plants to be effective and that should guide selection of species are outlined in Table 1.2.

The development of this methodology and the provision of necessary information about suitable types of plants required fundamental research into three components (Fig. 1.2):

1. identification of the prime locations for targeting revegetation, i.e. locate the erosion hotspots, flow pathways, and measure connectivity in the landscape at various scales;
2. identification of what plant species grow within the catchment and specifically in the erosion hotspots, then identification of the conditions required for their growth;
3. assessment and selection of the most effective plant species for establishing in the landscape to control erosion and increase sedimentation in specific locations.

The RECONDES project was developed to address these aims and undertake the research. It was funded by the European Commission in its Framework 6 programme (project no. GOCE-CT-2003-505361) as part of its concern with future effects of global and climate change and likely increased desertification threatening

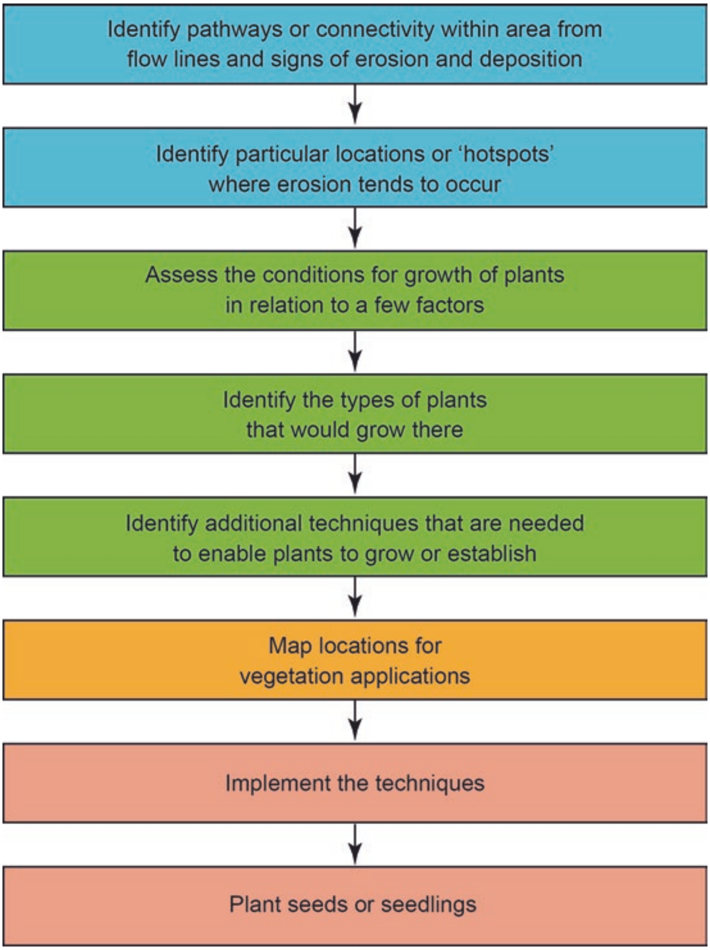

Fig. 1.1 Flow diagram of method of application of spatial vegetation strategy (After Hooke and Sandercock 2012)

Table 1.2 Desirable plant characteristics for erosion control

Properties
Native species
Germinates and/or propagates easily
Rapid growth rate
Perennial or persistent
Ability to grow in a range of substrates
Drought tolerant
Produces a dense root system
Has a high threshold to withstand forces of water flow
Ability to trap water and sediments

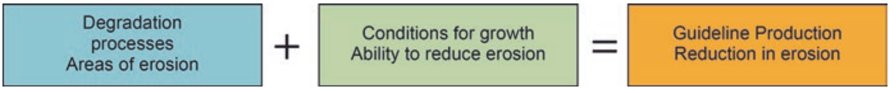

Fig. 1.2 Components of the research

Europe. A major objective of the project was to produce practical guidelines of how a spatially integrated approach to minimising erosion and sediment flux and mitigating desertification could be implemented. This was done by combining the results of the three research components. Methods have therefore been developed for investigating each of these components and for using the knowledge acquired.

The methods of identification of processes, hotspots and connectivity pathways and the results of measurements and analysis in this project are explained in Chap. 2. The identification of potential species growing in the area and their types of location, conditions for growth of those species including analysis of soil, edaphic, hydrological and other conditions, applied in the project are outlined in Chap. 3. Selection of the most suitable plants involves assessment of their effectiveness in reducing erosion and in increasing sedimentation. This may involve tests on the strength of the plants, both aerial and root parts, which can be done by experiments, laboratory and field measurements and involves field observations of the response and effects of plants in relation to flow events. The methods and results derived from this research are described in Chap. 4. A synthesis of the results illustrating their application in the various types of land unit commonly found in Mediterranean type landscapes is provided in Chap. 5. The wider implications and applicability are discussed.

The fundamental research on each of these aspects was carried out for an area in Southeast Spain and has produced new knowledge on conditions of plant growth and suitability of plants for erosion control in different locations within that environment. The specific findings on plants can be applied elsewhere in that region, with the same species, but wider application of this strategy in other regions with different species would require assessment of the suitability of local plants for implementation in the general approach (Fig. 1.1), either from available existing knowledge or from similar research to that outlined here. The purpose of this Springer Brief is therefore to explain the research methods adopted and to illustrate the research results and then to demonstrate the application of this approach and the production of the practical guidelines. Such research methods and this approach to land management could be implemented in other areas of the world vulnerable to desertification and land degradation.

1.5 Research Design and Study Area

Most of the research in RECONDES has been carried out in Southeast Spain, this being the driest and most vulnerable region in Europe to desertification. Cárcavo catchment in the northeast of the Region of Murcia (Fig. 1.3) was selected as the

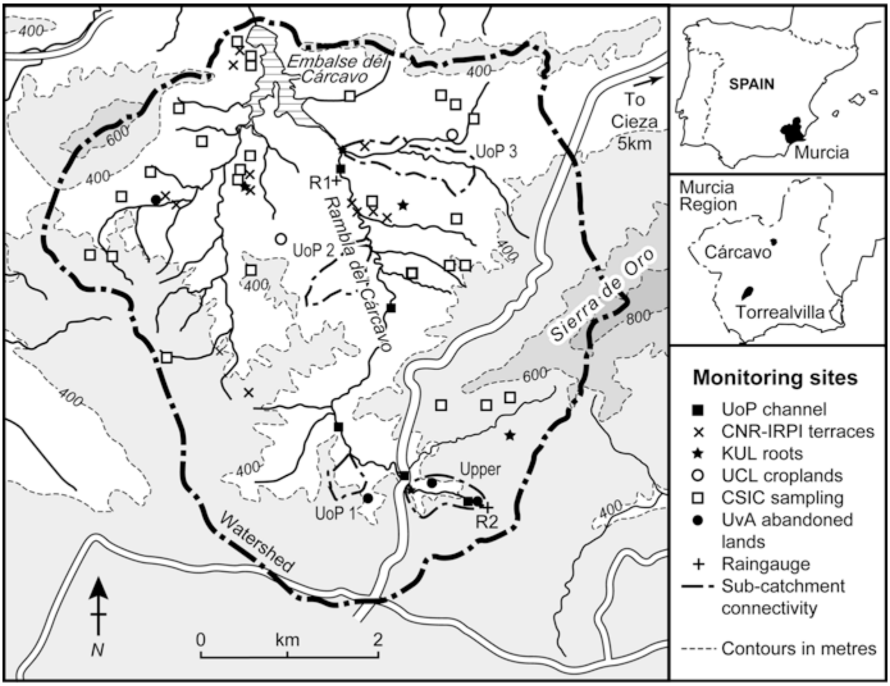

Fig. 1.3 Location of and characteristics of Cárcavo catchment and position of study sites and instrumentation

main catchment for all field work so as to maximise synergies and because it had the properties and conditions required (e.g. mixed land uses, marl lithology, extensive degraded land, management through forestation and check dams). Some work has also been completed in other catchments in Southeast Spain that had been previously studied in earlier projects and where long-term monitoring is still being carried out, particularly the Torrealvilla catchment in the Guadalentín basin in the southwest of the Region of Murcia.

1.5.1 General Catchment Characteristics

The Cárcavo basin is a small catchment of 30 km^2 and an altitude range between 220 and 850 m. This region of Spain is very dry with an average annual rainfall of 300 mm and a potential evapotranspiration of 900 mm. The geology of the area consists of steep Jurassic limestone and dolomite mountains with calcareous piedmonts, surrounding deposits of Cretaceous and Miocene marls, and Keuper gypsum deposits. The outlet of the basin drains directly into the Segura River, the major river system of southeastern Spain. The large difference of base level between the

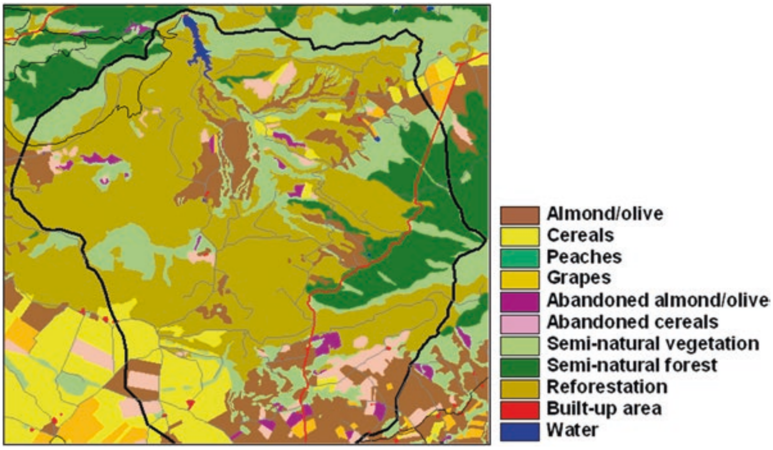

Fig. 1.4 Land use in Cárcavo catchment, 2004 (Authors: Cammeraat and Lesschen)

Segura River and the Cárcavo catchment is important in driving the erosive processes in the catchment. Indeed 'Cárcavo' in Spanish means gully. The catchment has a reservoir at its downstream end.

Most soils in the area are thin (Leptosols), weakly developed (Regosols) and mainly characterized by their parent material (Calcisols and Gypsisols). The current land use in the study area consists of cereals, grapes, olives, almonds, abandoned land, reforested land and semi-natural vegetation. In the 1970s large parts of degraded land were reforested with Aleppo pine (*Pinus halepensis* Mill.) within the framework of reforestation and soil conservation programmes. Some almond and olive fields in the central part are under irrigation, while low-yielding cereals are found on marls without irrigation. During the last 50 years, parts of the rainfed agriculture have been abandoned and are under different stages of secondary succession. The steeper and higher areas are under semi-natural vegetation and, on north slopes or gentle pediments, under forest.

Land use was mapped using digitisation of air photos and by field survey. Land use change was analysed from aerial photographs of 1985 and 1997. For 2004, the land use map of 1997 was updated during fieldwork in September 2004. Eleven different land use classes were distinguished of which six are related to agriculture. The created land use map for 2004 is shown in Fig. 1.4.

As can be seen from Fig. 1.4, a major part, especially the southeast part of the study area, is now almost completely under almond/olive, having replaced cereals in the period 1984–2004, with the area of abandoned cereals and almond/olive almost doubling during that time. Almost no land use changes occurred in the semi-natural and reforested areas during the last 30 years or more, since the reforestation programs are mainly from the 1970s.

Detailed sites for measurements and monitoring were set up within the Cárcavo catchment; the location of these sites is shown for different components of the study in Fig. 1.3. After the selection of field sites for specific purposes, equipment for monitoring runoff, sediment delivery and soil moisture was installed. At the main field site in the upper part of the catchment (Site 2, R2 on Fig.1.3) a tipping bucket, six FDR soil moisture sensors, three temperature sensors, two pressure transducers and several gypsum sensors, all connected to a data logger, were installed. Furthermore, 12 runoff indicators and two runoff gutters were placed at this site. One stand-alone pressure transducer was installed in the upper part of the Cárcavo channel, another one in a major tributary channel and a third in the lower part of the Cárcavo channel (Fig. 1.3), connected to a data logger and a tipping bucket rain gauge. Additionally, field sites in the Guadalentín basin in the south of Murcia province were being maintained, in the Torrealvilla basin and the Alqueria catchment where already a long term data record existed with regard to rainfall-runoff relationships at various scales (Cammeraat 2004; Cammeraat et al. 2009; Hooke 2007a). As rainfall events normally are very localised, more study areas where connectivity and runoff patterns were being monitored was considered useful.

1.5.2 Monitoring Programme and Hydrological Conditions

This research, involving field measurements and experiments, was carried out in the period 2004–2007. Below are details of the rainfall conditions in that period because this affected the number of events and the results it was possible to obtain.

In the Cárcavo basin two sites were maintained where rainfall was measured at 1-min interval. One site was located in the lower part of the catchment next to the main Cárcavo channel and the other is located in the southeast, in the upper part of the catchment at the upper abandoned lands site (Fig. 1.3). Rainfall was measured for more than 2 years and some statistics are given in Table 1.3. In general, the rainfall at the upper site is about 7 % higher than at the channel site, probably because of the higher altitude and rain shadow effect of the Sierra del Oro. The year 2005 was dry in Cárcavo with about 235 mm (20 % under the average) and very dry in the Guadalentín site with only 168 mm. In 2006 rainfall was about 50 % above the average in Cárcavo the deviation attributable to 160 mm of rain falling in the first days of November, as recorded at Site 2. Although the distance between the two measuring sites is only 4 km, the amount of rainfall recorded at each site varied considerably (Table 1.3).

For these events, in many cases there was a difference of at least 5 mm between the upper and lower parts, mainly related to autumn rainfall events, which are often torrential events with a high spatial variability (González-Hidalgo et al. 2001). For modelling purposes the spatial distribution of the rainfall is therefore very important, since no uniform rainfall can be expected for the whole catchment. This was also observed for the November 2006 event, where most erosion was observed in the southern (upper) part of the catchment.

During the first days of November 2006 in total about 160 mm of rainfall was measured at the rain gauge in the upper part of the catchment (Site 2). Most of this rainfall was of low intensity, only the last rainfall on 8 November was of high inten-

Table 1.3 Rainfall characteristics and statistics for both measuring sites in Cárcavo

	Channel site	Upper site
Altitude of rain gauge (m)	276	421
Sum rainfall 2005 (mm)	230	243
Sum rainfall 2006 (mm)	312[a]	446
Sum rainfall 2007 (till 19 March) (mm)	106	117
Sum of rainfall without missing data (mm)	482	514
Number of events of >1 mm	63	72
Number of events of >10 mm	13	15
Number of events of >20 mm	7	6

[a]Due to malfunctioning of the rain gauge the November 2006 event is not recorded at the channel site, and therefore total rainfall is underestimated

sity with 37 mm within 3 h and a maximum intensity of 50 mm/h within a 10 min interval. The recurrence time of the event of 8 November was about 2 years, based on a 36-year data series of daily rainfall at the Almadenes weather station, located just north of the catchment near Cieza. However, when the rainfall of the previous days was taken into account the recurrence time for the 10-day rainfall sum was 23 years. Since the soil was already saturated after the rainfall of the previous days this event caused significant erosion, which was observed by completely filled sediment boxes, a reaction of all runoff indicators, rills on agricultural fields, failure of some terraces, and a flow in the lower part of the channel of approximately 60 cm height.

If the rainfall for the study period 2004–2007 is compared with the longer-term record the project period is seen as particularly dry (Hooke and Mant 2015). Certainly the total rainfall in the whole region was below average for the whole study period. This did restrict the number of rainfall events it was possible to measure and particularly the number of intense rainfall events, the November 2006 event being the exception. The infrequent occurrence of rainfall events in semi-arid areas and their localised spatial extent is a problem for all such monitoring and research programmes. Ideally, extended periods or monitoring of several catchments is needed but this is often not feasible in research programmes.

1.6 Conclusion

This chapter has set out the major premises of the approach developed to use vegetation to mitigate desertification and reduce soil erosion and land degradation by reduction of connectivity in the landscape. It has explained the overall research design used and the mode of application in the study area in Southeast Spain. The following three chapters explain the methods and results for each of the major components of the research. These are synthesised and developed into practical recommendations in Chap. 5.