Multi-scale interactions between soil, vegetation and erosion in the context of agricultural land abandonment in a semi-arid environment

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1. Introduction

1.1. Research framework

The title of this thesis is “Multi-scale interactions between soil, vegetation and erosion in the context of agricultural land abandonment in a semi-arid environment”. This title represents the three main themes of this thesis, which are soil erosion, scale issues and agricultural land abandonment. Soil erosion is one of the main environmental problems in Mediterranean countries which increases desertification and results in soil quality loss and off-site effects such as flash floods and reservoir sedimentation (Poesen and Hooke, 1997). For the mitigation of soil erosion it is important to understand the mechanisms and the critical soil conditions that are necessary for maintaining and restoring soil quality. Vegetation is one of the key factors that controls soil erosion and which can be used for the mitigation of soil erosion by reducing the connectivity of water and sediment (Thornes, 1990). The second theme is scale, which has a spatial as well as temporal dimension and together they determine which erosion processes are relevant. The spatial scales in this research range from plot to a third order catchment and the temporal scales from minutes to decades. One of the aims of this thesis is to link plot scale observations with catchment scale erosion modelling. The third central theme of this thesis is agricultural land abandonment, which is one of the main changes in land use in marginal areas of northern Mediterranean countries. However, about the consequences of land abandonment not much is known. On the one hand an increase in vegetation cover can decrease erosion, but on the other hand existing soil and water conservation structures are no longer maintained, which can increase erosion. Semi-natural landscapes in dynamic equilibrium are considered to be stable and will have relatively low erosion rates. However, changes in land use such as agricultural land abandonment will disrupt the (in this case artificial) equilibrium. Physical and biological processes will adapt to the new situation, which can lead to an increase or activation of erosion processes, e.g. the spontaneous reorganisation of no longer preserved artificial drainage networks (Gallart et al., 1994). These three themes will be further discussed in the background section of in this introduction and will come back in the different chapters of this thesis.

This research was carried out at the University of Amsterdam and was part of the RECONDES project, a three year EU-project coordinated by the University of Portsmouth. Other partners in the project were the Katholieke Universiteit Leuven and the Université Catholique de Louvain from Belgium, CSIC-CEBAS from Spain and CNR-IRPI from Italy. The focus of RECONDES was to address the mitigation of desertification processes by the means of innovative techniques using vegetation in specific landscape configurations prone
to severe degradation processes. Its major objective was to produce practical guidelines on the conditions for use of vegetation in areas vulnerable to desertification, taking into account spatial variability in geomorphological and human-driven processes related to degradation and desertification. Most of the research was carried out at the Carcavo basin, a 30 km² catchment in Southeast Spain.

Soil erosion is a very broad research field with inputs from many different disciplines, ranging from meteorology for the analysis of extreme rainfall events to social sciences for the study of socio-economic factors that determine land use dynamics. Four main factors can be distinguished that influence erosion: erosivity (rainfall characteristics), erodibility (soil properties), slope (topography) and plant cover (Morgan, 1995). However, these factors are determined by many different physical, biological and socio-economical processes that occur on different spatial and temporal scales. Since one cannot study all aspects related to soil erosion a clear definition of the research framework is essential. Primarily the hierarchical framework of the RECONDES project is followed with a focus on the erosion processes that occur on abandoned land. However, the other land units were included for the catchment scale component of this thesis, but processes within these land units were not studied in detail. Soil erosion processes on agricultural land were studied in more detail by the University of Louvain (e.g. Van Wesemael et al., 2006), erosion in channels was studied by the University of Portsmouth (e.g. Sandercock et al., 2007) and the effects of plant roots on rill and gully erosion was studied by the University of Leuven (e.g. De Baets et al., 2007). Hence, the main focus of this thesis will be on soil erosion processes on abandoned land at multiple scales. The concept of hydrological connectivity (Bracken and Croke, 2007) will be used to link the different spatial scale levels that range from plot to catchment.

1.2. Background

1.2.1. Soil erosion
Spain is one of the countries that is most severely affected by soil erosion in Europe. The presence of highly erodible soils, a relatively steep topography, periods of drought and torrential rainfall explain the high erosion risk in Spain (Solé Benet, 2006). Additionally, a long history of anthropogenic disturbances such as deforestation and agriculture on marginal lands accelerated soil erosion processes and led to the loss of well-developed soils in the Mediterranean. Nowadays many mountain slopes are bare and valleys are filled with sediment (Yaalon, 1997). In the Region of Murcia 46 percent of the total area was classified as soils with high or very high erosion risk (Región de Murcia, 2002). Soils in the semi-arid parts of the Mediterranean are especially vulnerable to erosion because of low vegetation.
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Cover and the occurrence of high intensity rainfall events. Kosmas et al. (1997) showed that runoff and sediment losses on hilly Mediterranean shrublands increased with decreasing annual rainfall, until a maximum at 280-300 mm, which could be attributed to a decrease in vegetation cover. In semi-arid areas overland flow normally occurs when rainfall intensity exceeds the rate at which water infiltrates into the soil (Hortonian overland flow). Once flow becomes concentrated its velocity and erosive force increase and rill and gully erosion become the main erosion processes. Recent studies indicate that gully erosion is one of the main erosion processes in terms of sediment production (Poesen and Valentín, 2003).

The problems caused by soil erosion can be divided into on-site and off-site effects. Soil fertility loss due to the removal of fertile topsoil is the main on-site effect, but also deterioration of soil physical properties, which reduces infiltration and enhances further erosion, is a negative on-site effect. The increased amounts of water and sediment that are transported downwards through the catchment can lead to flash floods and reservoir sedimentation downstream. Flood events in the Mediterranean region are characterized by an extremely rapid rise in the discharge, which is one of the reasons that these events tend to be so devastating and dangerous. These floods are often very localized and typically peak flows decrease downstream from the zone of the storm due to transmission losses (Poesen and Hooke, 1997). For Spain an increase in the frequency of these torrential rainfall events is observed (Alpert et al., 2002). Apart from rainfall characteristics also the physical characteristics of a basin such as steep slopes, sparse vegetation, thin soils and permeable rocks determine the generation of flash floods (Camarasa Belmonte and Segura Beltran, 2001). A second off-site effect is sedimentation of reservoirs and corresponding loss in water storage capacity. The annual loss in storage capacity of many reservoirs due to sediment deposition can be up to five percent, which means that the majority of the capacity is lost after only 25 years. These high rates of storage loss pose a serious threat to the economic sustainability of the reservoir (Verstraeten et al., 2003). For example the Puentes dam in the Guadalentín, about 50 km south of the Carcavo basin, has been raised already three times in the last 150 years due to sedimentation of the reservoir.

In Mediterranean environments the interactions between soil and vegetation have a major influence on soil erosion. Vegetation protects the soil because the canopy and litter intercept raindrops and reduce their kinetic energy. Furthermore, vegetation has a positive influence on soil quality due to the organic matter input by litter. Vegetation also increases chemical weathering, enhances infiltration and favours a less contrasted microclimate. These conditions generate a more active fauna and flora, and consequently soil structure and other soil physical properties such as soil aggregation, water storage capacity and porosity are improved. All these positive influences of vegetation lower the erodibility and decrease the risk of soil erosion (Bochet et al., 1999; Cammeraat and Imeson, 1999).
Vegetation in semi-arid environments is characterised by heterogeneous patterns of bare soil and vegetation patches (Valentin et al., 1999). This mosaic of vegetated and bare zones makes overland flow highly discontinuous as a result of the non-uniform infiltration (Cerdà, 1998; Puigdefabregas et al., 1999). The bare patches between plants function as runoff generating areas, generally bare rock and crusted areas that are characterised by poor soil structure with low infiltration rates, whereas the vegetated patches function as runoff sinks.

To mitigate soil erosion several soil and water conservation practices are applied in the Mediterranean. On agricultural land cover crops are often used to protect the soil against erosion, but also for fertilisation as green manure. Winter wheat and other cereals are most popular. However, under perennials the use of cover crops is very low, because farmers prefer fresh bare soil for higher infiltration and to avoid competition for water (Pastor, 2004). Conservation tillage is therefore hardly adopted in these areas. Moreover, zero-tillage on soils that are vulnerable to crusting, e.g. marly soils, might even enhance erosion due to increased runoff. In stony soils conventional tillage can increase the rock fragment cover at the soil surface, which functions as a mulch layer (Oostwoud Wijdenes et al., 1997). Revegetation is one of the main techniques to control erosion on gullied areas, landslides, road embankments and quarries. To mitigate gully erosion, natural vegetation with well-developed roots should be (re)established in concentrated flow zones affected by gully erosion. This will decrease soil loss and sediment production and the connectivity in the landscape will be interrupted resulting in a lower sediment delivery to valley bottoms or river channels (Poesen et al., 2003). The use of vegetation for mitigation of erosion was also the focus of the RECONDES project. In the Mediterranean terracing is the most widely used measure for soil conservation. The original aim of terracing is to reduce soil erosion and to intercept runoff by decreasing the general slope (Morgan, 1995). However, expansion and mechanisation of tree crop plantations since the nineties lead to the removal of terraces and increased tillage erosion (Van Wesemael et al., 2006; Borselli et al., 2006). In Spain the construction of checkdams in ephemeral channels of low order catchments in combination with reforestation of degraded hillslopes is the traditional way to mitigate erosion by the Spanish Forest Administration. The small dams are supposed to stabilise the channels and reduce erosion. However, besides their positive upstream effects of sediment storage and channel stabilisation, the dams also cause erosion downstream (Castillo et al., 2007).

1.2.2. Scale issues in soil erosion research
In soil erosion research the issue of scale is very important since different processes control erosion at the various spatial as well as temporal scales, which leads to different runoff and erosion rates. Results obtained at one scale are therefore not representative for other scales, since the different processes are not taken into account. For example plot scale studies do
not consider gully erosion, while at catchment scale most of the sediment yield is often produced by gully erosion. Erosion processes are therefore generally non-linear and scale dependent. This scale dependency has also lead to a separation in soil erosion research, which can roughly be divided in detailed plot scale studies and general catchment scale studies. Plot scale studies are based on techniques such as Gerlach troughs at open plots, rainfall simulation experiments, erosion pins, USLE based bounded plots, Cesium-137 measurements or laboratory experiments. Whereas catchment scale studies are often based on sediment yields from reservoirs, discharge measurements or remote sensing imagery (Solé Benet, 2006). However, these two types of soil erosion studies are often not combined, which makes that general catchment studies lack the information from relevant process at finer scales, while plot scale studies are often too detailed to be applied at broader scales. The same holds true for erosion models, where detailed erosion models, e.g. EUROSEM or WEPP, require so much input data, that it becomes almost impossible to use these models at broader spatial scales. An overview of European soil erosion models is given by Jetten and Favis-Mortlock (2006), who discussed the model’s approaches and the spatial and temporal scales at which they are applied.

Several studies have experimentally demonstrated scale dependency with in general decreasing area specific runoff and erosion rates (e.g. Cammeraat, 2002; Wilcox et al., 2003; De Vente and Poesen 2005). This decrease can be partly attributed to the influences of sinks, i.e. areas of infiltration and sedimentation, such as increased infiltration under vegetation, sediment deposition and infiltration on agricultural terraces and sedimentation in reservoirs. The connectivity between the different sources and sinks of runoff and sediment determines the impact and magnitude of runoff and erosion at broader scales. Also the temporal dimension is important to consider, since extreme events, which have a long recurrence time, are known to contribute substantially to total erosion and landscape formation, particularly in semi-arid landscapes (Boardman, 2006). Only continued monitoring over long time scales can include the effects of these extreme events (Boardman, 2003). Short-term monitoring studies are therefore not very suitable for the assessment of long-term erosion rates.

Schulze (2000) identified six causes of scale problems from a hydrological perspective: spatial heterogeneity in surface process, non-linearity in response, processes require threshold scales to occur, dominant processes change with scale, development of emerging properties and disturbance regimes. These six causes are shortly explained below in the context of soil erosion. Landscapes are characterised by spatial heterogeneity which influences soil erosion processes, this variability is manifested in topography (e.g. slope and position), soils (e.g. infiltration capacity and crusting), rainfall (e.g. intensity and frequency) and land use (e.g. vegetation cover and root type). Erosion processes act at
different time scales (minutes to millennia) and with different rates (e.g. splash erosion versus piping), which makes the responses highly non-linear. Runoff generation and erosion processes are subject to thresholds, which are determined by the physical characteristics of a landscape and human interventions (e.g. check dam construction) and these thresholds are scale dependent (Cammeraat, 2004). Furthermore, the dominant erosion processes change with spatial scale, e.g. gully and bank erosion are dominant at catchment scale, while splash and sheet erosion are the main processes at plot scale. Emerging properties can arise from the interaction of small-scale properties, which have a different influence at large scale compared to the small scale, e.g. field boundaries can form important thresholds for erosion at hillslope scale, but the influence at plot scale is insignificant. Disturbance regimes are the last cause of scale problems, for example changes in land use or the construction of dams. All these reasons make upscaling of soil erosion processes very complicated.

Several approaches for scaling of geomorphological processes can be distinguished. However, all approaches have their disadvantages and biophysical processes remain ‘pseudo represented’, which makes the problem of upscaling still a largely unsolved one (Schulze, 2000). The most basic approach is extrapolation, which is used to scale up point measurements to larger areas under the assumption that spatial variability can be neglected. However, this assumption is generally not valid, especially not for semi-arid areas with their heterogeneous vegetation patterns and non-linear system responses. A second approach is a lumped model which considers the area of interest (e.g. catchment) as a single entity for which the spatial variables (e.g. soils, land use) are averaged and the model parameters are calibrated until the observations are reproduced. However, such a lumped model is only representative for the calibrated conditions and cannot be directly applied to other areas or for other time scales. A third approach is a distributed model in which processes observed at point scale are represented by relatively homogeneous units, called response units or hydrological similar surfaces (England and Stephenson, 1970; Cammeraat, 2002; Kirkby et al., 2002). A disadvantage of this approach is the ambiguity to which degree these response units have to be disaggregated to commence the upscaling. A last approach is modelling at fine enough resolution, however, high data requirements and changing erosion processes with scale make also this approach not the solution for upscaling (Schulze, 2000).

In ecology the hierarchy theory is often used for scaling issues (O’Neill et al., 1986). In this approach a specific scale of interest is selected and finer-scale processes are incorporated in a nested hierarchy. This concept was also used by Cammeraat (2002) in combination with response units. He studied and quantified the hydrological and erosional response of watersheds and its sub-systems based on a nested measurement approach in a first order
drainage basin in Southeast Spain. The outcomes demonstrate the strong influence of both spatial and temporal scale on the generation of runoff (Figure 1.1). At plot scale the average threshold for runoff generation was 15 mm of rainfall, while the threshold for runoff generation at watershed scale was about 33 mm. Consequently, the threshold for runoff generation increases with catchment size. Figure 1.1 also shows the temporal dimension of runoff occurrence, which is strongly related to the recurrence period (Cammeraat, 2004). This example of runoff generation demonstrates the importance of both spatial and temporal scale in soil erosion research.

![Figure 1.1. Threshold rainfall depth required to generate runoff at different scales within a catchment in Southeast Spain for a three-year period (adapted from Cammeraat (2002) with permission from © John Wiley & Sons Limited)](image)

1.2.3. Agricultural land abandonment

Land abandonment is widespread in Europe and the influence of environmental changes is unpredictable due to environmental, agricultural and socio-economic contextual factors (MacDonald et al., 2000). Although land abandonment occurs in the whole Mediterranean Basin, e.g. France (Taillefumier and Piégay, 2003), Portugal (Pinto-Correia and Mascarenhas, 1999), Italy (Blasi et al., 2000), Greece (Kosmas et al., 2000) and Israel (Neeman and Izhaki, 1996), most literature is available for Spain, where abandonment of agricultural land is nowadays widely spread (Fernandez-Ales et al., 1992; MacDonald et al., 2000; Geeson et al., 2002). Abandoned land is in this thesis defined as areas previously cultivated but now abandoned and where the natural vegetation has been allowed to grow.
under various intensities of grazing (Kosmas et al., 2002). This definition is used since in most parts of the Mediterranean almost all natural vegetation is grazed to some extent by migrating or permanent flocks of goats and sheep (Clark, 1996).

Already since Roman times land use in Spain has been changing due to human influences. Forest clearing, reclamation and terracing of vast areas around the population centres took place mainly in the 17th and 18th centuries as a consequence of high population pressure (Ruecker et al., 1998). The greatest land use changes in Spain took place at the end of the 18th century, when the laws of the ‘confiscation’ were enforced. The sale of common lands from 1859 onwards resulted in continuous large-scale clearing of forests and the development of other land uses. In the 1950s the irrigated area increased rapidly, as a consequence of the regulations of river water and the initiation of groundwater extraction (Barberá et al., 1997). This and the beginning of intensification and industrialization of agriculture resulted in massive abandonment of non-mechanisable and marginal areas in the 1950s and 1960s. Initially land abandonment occurred in the most economically developed regions and later throughout the whole country. The area cultivated with cereals decreased drastically, while the area with perennials as olives, almonds and especially citrus increased (Romero Díaz et al., 2002). Land abandonment continued with further economic development, as result of increased importance of tourism and industrialisation. Nowadays intensive agricultural systems are concentrated in the more fertile areas, while marginal areas are under extensive agriculture or have been abandoned (Fernandez Ales et al., 1992). Agricultural land abandonment is expected to increase in the future in many areas of the Mediterranean, as a consequence of changing EU-policies, urbanisation, globalisation, desertification and climate change, which is also projected by different land use change scenarios (Olesen and Bindi, 2002; Rounsevell et al., 2006; Verburg et al., 2006). Most climate change scenarios predict less and more irregular rainfall in the Mediterranean area (Christensen et al., 2007), which will reduce the agricultural productivity in Mediterranean region and lead to increased extensification. However, the recent demand for biofuels might slow down the increase of land abandonment (Hoogwijk et al., 2005). Nevertheless, semi-arid areas like the Carcavo basin probably remain too dry for economically profitable production of crops for food or biofuels.

When abandoned agricultural land is no longer influenced by human activities the secondary succession can start. The development of the vegetation succession depends much on local environmental and ecological factors, especially rainfall and seed dispersal are limiting factors (Pugnaire et al., 2006). In general annual plants and short-lived perennials are dominant during the first phase of abandonment (3-5 years) with a higher cover and species richness (Obando, 2002). In the second phase forbs and dwarf scrubs appear, while perennial grasses and shrubs start to increase after 10 years of abandonment.
(Bonet, 2004). *Quercus ilex* dominated shrublands (*Rhamno lycioidis-Quercetum cocciferae*) are considered to be the terminal point of secondary succession in extensive areas of the Mediterranean (Romero-Calcerrada and Perry, 2004). However, in many degraded areas this final stage will not be reached and *Stipa tenecissima* and dwarf shrub communities form the main vegetation on these long abandoned fields. Biodiversity in Mediterranean ecosystems is generally in decline as a consequence of land abandonment in marginal areas and intensification of agriculture and forestry in other areas (Romero-Calcerrada and Perry, 2004; Moreira and Russo, 2007). Reestablishment of natural shrubland in revegetation programs for abandoned agricultural lands has therefore been encouraged by the agricultural policies of the European Union as a means for regenerating the biodiversity of these areas (Caravaca et al., 2003).

The changing vegetation cover and composition after abandonment will also affect soil properties. In general soil quality will improve as a result of the positive influence of vegetation. Studies showed that important soil properties such as organic matter content and aggregate stability increase with time of abandonment (Cammeraat and Imeson, 1998; Kosmas et al., 2000; Dunjó et al., 2003). The recovery of vegetation and improved soil properties will make the soil less vulnerable to erosion. However, the rate of recovery is highly dependent on the amount of rainfall. In more humid parts of Spain a decrease in erosion after land abandonment is observed (García-Ruiz et al., 1996; Molinillo et al., 1997), while erosion in semi-arid areas such as Southeast Spain increased during the first years/decades after abandonment (Cerdà, 1997; Bull et al., 2000; Lasanta et al., 2000). This increase in soil erosion during the first years can be explained by the deteriorated soil properties and still low vegetation cover. Furthermore, soil and water conservation structures are no longer maintained and the original drainage pattern might be restored, which might lead to terrace failure and gully erosion (Gallart et al., 1994; Cammeraat et al., 2005).

### 1.3. Objectives and research questions

The general objective of this thesis is to study the interactions between soil, vegetation and erosion in the context of agricultural land abandonment at multiple scales in a semi-arid environment. This objective combines the three central themes of this thesis, i.e. soil erosion, scale issues and agricultural land abandonment. To connect the different chapters and to focus on the central themes of this thesis three main key research questions have been formulated.
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1. Where does agricultural land abandonment occur and how do vegetation and soil properties change after abandonment?
2. Which are the main soil erosion processes on abandoned land and how to mitigate them?
3. How to integrate plot and hillslope scale influences in runoff and erosion modelling at catchment scale?

Besides the general objective and research questions each chapter deals with a separate topic related to one or more of the central themes. Together these chapters contribute to the main objective and research questions of this thesis. The following objectives were defined for each chapter:

Chapter 2: To identify vulnerable areas for gully erosion using different scenarios of land abandonment.
Chapter 3: To investigate the development of spatial heterogeneity in vegetation and soil properties after land abandonment.
Chapter 4: To assess the extent and causes of erosion and terrace failure on abandoned fields and to discuss options for mitigation.
Chapter 5: To evaluate which vegetation index is most suitable for upscaling fractional vegetation cover in a semi-arid environment using a high resolution QuickBird image.
Chapter 6: To model runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity.

1.4. Study area description

The Carcavo basin in Southeast Spain was used as study area, since this catchment was selected as study site in Southeast Spain for the RECONDES project. This catchment fulfilled the various criteria that were established for identification of suitable catchments, which were a moderate size of circa 25 km², variation in land use, presence of channels, dominance in marl bedrock, availability of some base data and prior knowledge and reasonably accessible.

1.4.1. Topographical setting
The Carcavo basin is located about 40 km northwest of the city of Murcia in Southeast Spain, near the town of Cieza (38°13’ N; 1°31’ W). It is a third order catchment of 30 km² with altitudes ranging from 220 to 850 meter above sea level (Figure 1.2). The basin is characterised by two steep mountain ridges, the Sierra del Almorchon in the northwest and
the Sierra del Oro in the eastern part of the catchment. The outlet of the basin drains directly into the Segura River, the major river system of southeast Spain. The large difference in base level between the Segura River and the Carcavo catchment is an important driver for erosive processes, which lead to deeply incised channels in the catchment. Indeed “Carcavo” in Spanish means gully.

1.4.2. Climate

The Carcavo Basin is located in the rain shadow of the Betic ranges and this region forms one of the driest areas of Europe. Climate is predominantly Mediterranean semi-arid and ecosystems have to cope with water stress. Average yearly rainfall is just around 300 mm, while the potential evapotranspiration, as measured by the Thornthwaite method, is close to 900 mm. However, the variability between years is very high with a minimum of 125 mm and a maximum of almost 700 mm (Figure 1.3), as measured at the Almadenes weather station, which is located just north of the Carcavo basin. The average annual temperature is 16.5°C with January being the coldest month with an average temperature of 9.5°C and July and August the hottest with average temperatures near 26°C. Frost is relatively uncommon and rarely severe. Intra-annual droughts, typical of Mediterranean climate, are severe. In July and most of August there is virtually no rain, and extended periods of 5 months or
more of very low or no rainfall are common. The rainfall regime is bimodal with most rainfall in April and October. Especially autumn rains can be very intense, when the Mediterranean Sea is still warm and humid air from the east can lead to a very unstable atmosphere due to convective and orographic effects. Under these conditions very intense rainstorms (gota fria) can locally from that do most of the geomorphological work (Poesen and Hooke, 1997). In October 1973 the nearby Guadalentín basin was struck by such an extreme event, with 350 mm of rain within 10 hours, which resulted in a flash flood that killed 96 people. In various vulnerable catchments dams and reservoirs were constructed to reduce the risk on flash flood in downstream areas. A barrier dam was also constructed at the outlet of the Carcavo basin in the late eighties.

![Graph](image)

**Figure 1.3.** Annual and daily maximum precipitation for the Almadenes weather station

### 1.4.3. Geology and geomorphology

The Carcavo basin is located in a complex geological setting within the external zone of the Betic Cordillera. Two important fault systems border the catchment, at the northern border the Linea Electrica fault, which is an east to west oriented strike-slip fault and the Crevillente fault south of the catchment, which is a southwest to northeast oriented strike-slip fault. The Crevillente fault system divides the internal and the external zone (Biermann, 1995; Nieto and Rey, 2004). The internal zone is situated south of this fault system and consists mainly of metamorphic rocks, whereas the external zone is situated north of the fault zone and consists of sedimentary rocks. The zone between the Crevillente fault and
the Linea Electrica fault is the Subbetic zone to which the Carcavo basin belongs, consequently calcareous sedimentary rocks are found.

During the late Burdigalian (early to middle Miocene) the oblique collision of the African plate against Iberia caused strike-slip deformation. This resulted in basin subsidence and uplift of independent units in the fault zone. The Carcavo basin was one of the basins that subsided, which lead to the formation of marine marls, sandstones and conglomerates during the Tortonian. These marls are currently folded and deformed due to Pliocene tectonic activity along the main faults. Also diapirism of the plastic underlying Keuper marls caused deformation and subsidence of the Tortonian marls. At present the resistant sandstone and conglomerate ridges are located along the edges of the Tortonian substrate. The southern part of the catchment was in the past not connected to the northern part and drained to the south. During the Late Pleistocene this part became connected due to backward erosion of the Carcavo channel. The capturing of the southern part could be deduced from the sudden supply of large amounts of distal fine material to an extensive area in the northern part and the disconnection between the Middle Pleistocene colluvial deposits at the southern footslopes of the Sierra del Oro (Van Gorp, 2006). During the Quaternary continuing neo-tectonic activity and sea levels changes lead to lowering of the Segura river bed (Faust, 1997). In response to this base level lowering the Carcavo channel started to incise and especially the northern part of the catchment is now dominated by incision patterns, whereas the incision in the southern part is not so strongly expressed, due to the relatively late connecting to the main Carcavo basin. At present, the catchment is still reacting to the last base level lowering, which causes incision and mass movement in the entire Carcavo basin.

In the Carcavo basin five main geological units can be distinguished. The oldest are of Triassic age consisting of Muschelkalk carbonate rocks and highly deformed gypsiferous Keuper marls. The highest parts of the basin consist of Jurassic limestones and dolomites, which are the Sierra del Almorchon in the northwest and the Sierra del Oro in the eastern part of the catchment. In the southeast of the basin deformed marls, limestone and sandstone of Cretaceous age are the main lithology. The centre of the basin consists of Miocene basin fills, which are mainly marls and some sandstones and conglomerates. The last geological unit that can be distinguished are the Quaternary slope deposits, which overly the Miocene and Cretaceous formations. In these Quaternary deposits several surface levels can be distinguished, which represent the different periods of geomorphological activity. Van Gorp (2006) mapped four surface levels at the footslopes of the Sierra del Oro and Sierra del Almorchon, and two terrace levels along the Carcavo channel.
Within the Carcavo basin several well developed pediments are present, of which the highest two levels are covered by calcretes. Pediments are slightly sloping areas, mainly developed in bedrock or covered with a thin covering of colluvial materials on top and connected to the steeper headwalls of hills and mountains. These pediments are characteristic for long term landscape development in semi-arid environments (Cooke et al., 1993). Pediments covered by calcretes are stable landforms due to the protective caprock function of the calcrete (Alonso-Zarza et al., 1998). Calcretes are pedogenetic horizons that are cemented by calcium carbonate. In the semi-arid area of southeast Spain many calcretes are present, which have been formed during different stages of the Pleistocene. Under semi-arid to semi-humid conditions (300-600 mm rainfall) soil formation occurs and a petrocalcic horizon can develop in the subsoil. When the climate becomes more arid, the top layer denudates and the petrocalcic horizon becomes exposed to the surface and protects the underlying substrate against further erosion (Blümel, 1986).

1.4.4. Soils and soil properties

In general soils in the Mediterranean on relatively stable surfaces are characterised by a large proportion of limestone and other calcareous rocks as parent material, moderate weathering, hematite-induced reddening of clays and carbonate dissolution and reprecipitation with prevalence of calcic horizons (Yaalon, 1997). However, within the Carcavo basin four main soil types occur, these are Leptosols on the limestone and dolomite mountains and outcrops, Calcisols on the pediments of the Sierra del Almorchon and Sierra del Oro, Regosols on the marls and Gypsisols on the gypsiferous Keuper marls. Soil formation is limited due to the semi-arid climate and the steep topography with subsequent high erosion rates, resulting in mostly shallow soils, i.e. Leptosols and Regosols. As a consequence lithology is the main soil forming factor and the distribution of soil types is strongly linked to it. Soils in the Mediterranean are often susceptible to water erosion, due to low organic matter content, large silt fraction, poor soil structure and weak aggregate stability, which leads to surface sealing during intense rainfall (Ramos et al., 2000). These soil crusts reduce infiltration rates and may increase runoff and consequently erosion. Significant differences in erodibility are found among lithologies with marls as most erodible material (Albaladejo et al., 1995; Cerdà, 1999). Marl is also one of the main substrates in the Carcavo basin with an occurrence of 60 percent, and even 77 percent when the gypsiferous Keuper marls are included, which makes the catchment in combination with the sparse vegetation cover vulnerable to erosion.

The spatial distribution of soil properties in semi-natural areas is often very heterogeneous under semi-arid conditions due to patchiness of the vegetation. The higher organic matter input by litter favours soil aggregation and soil faunal activity, which both increase macro-porosity and infiltration rates and lower surface compaction. Also the micro-climate under
vegetation with lower temperature amplitudes and more shading is favourable, resulting in better soil moisture conditions than for bare soil (Bochet et al., 1999; Maestre and Cortina, 2002). All these characteristics lower the soil erodibility and decrease the erosion risk. Under vegetation also other chemical soil properties such as nutrient content and cation exchange capacity increases. The increased heterogeneity of soil resources is also known as the “islands of fertility” phenomenon (Schlesinger et al., 1990). Organic carbon content is generally the best indication for soil quality because of its influence on soil structure, water holding capacity and CEC, since most soils in the Mediterranean are often water limited instead of nutrient limited.

Besides the chemical and physical properties of the soil, several other factors such as rock fragments, biological soil crusts and water repellency, influence the hydrological and erosion response of a soil as well. The presence of rock fragments in the soil has significant effects on the infiltration and the water storage capacity of the soil as well as on the soil surface. As rock fragments are usually present at the surface it is important to notice whether these are positioned at the surface or are embedded in the soil surface crust. In the latter case infiltration is reduced, whereas in the first case infiltration is increased (Poesen and Lavee, 1994). Biological or cryptogamic soil crusts, which are thin crusts made up of mosses, lichens, algae, and bacteria, are another typical feature in semi-arid ecosystems. These organisms can form a resistant biotic layer in bare areas in undisturbed arid and semi-arid lands. They form a cryptogamic crust that helps to protect soil material from erosion, absorbs moisture, and provides nitrogen and other nutrients for plant growth (Harper and Marble, 1988; Belnap, 2006). Another property of many Mediterranean soils, especially coarse textured soils, is their water repellency, which has substantial hydrological and geomorphological repercussions. Reduced infiltration capacity, enhanced overland flow, accelerated soil erosion and development of preferential flow paths in the soil are the main effects. Hydrophobicity is caused by organic coatings of long-chained organic molecules, released from decomposing or burning plant litter, micro-organisms, fungal growth or root zone and leaf surfaces of living plants (Doerr et al., 2000). It is shown that several Mediterranean vegetation species commonly occurring in the study area have different degrees of hydrophobicity (Verheijen and Cammeraat, 2007).

1.4.5. Land use
Due to its topographical setting and the lack of human habitation the Carcavo basin is mainly used for extensive agriculture and reforestation. The current land use in the study area consists of cereals, olive and almond orchards, vineyards, abandoned land, reforested land and semi-natural vegetation. The north slopes of the Sierra del Oro and Sierra del Almorchon, which receive less radiation, can sustain a semi-natural pine forest, while other semi-natural areas consist of shrublands and \textit{Stipa tenecissima} dominated rangelands.
Agriculture is mainly situated on the plains, wide streambeds and terraced hillslopes. Within the Carcavo basin few houses are located, but most of them have been abandoned and are now ruins. Livestock is only a marginal agricultural activity with two small mixed sheep and goat flocks that pass the area now and then to graze on marginal agriculture fields and semi-natural areas. Close to the outlet of the catchment a barrier dam was built in the late eighties for the purpose of flood control. Irrigation possibilities within the catchment are limited and only few water basins have been constructed during the last years. These are fed by local wells and groundwater and are mainly used for olives. However, some almond orchards are occasionally irrigated as well. Just north of the basin, in the valley of the Segura river, intensive irrigation systems exists for peach orchards.

Three different stages in the agricultural history of the Carcavo basin can be distinguished. The first half of the twentieth century was characterized by an extension of traditional dryland crops and livestock in the catchment. From 1950s to 1980s agriculture suffered and there was large scale land abandonment due to general socio-economic factors relating to the marginal areas in Spain (Fernandez-Ales et al., 1992; Barberá et al., 1997). Strong migration from the rural areas to the cities took place at the same time as government reforestation projects tried to recover abandoned land. In the Carcavo basin large parts of degraded rangeland were reforested with pine (Pinus halepensis) during the 1970s for reforestation and soil conservation purposes. Nowadays these reforested lands make up almost 45 percent of the total area, while croplands occupy about 29 percent. The last stage of land use change is the conversion of rainfed cereals to almonds, olives and vineyards since the eighties. Especially almond orchards, which are more drought tolerant, have replaced cereals and are now dominant in the southeastern part of the catchment. In addition, parts of the non-irrigated agriculture have been abandoned during the last decades and are now under different stages of secondary vegetation succession.

1.4.6. Vegetation

The flora of Southeast Spain is characterised by an exceptional richness and is very abundant in endemic and Iberian-Mauritanian species (Peinado et al., 1992). Within the Murcia Region 292 associations and communities are described, which is higher than many Spanish or European similarly sized territories (Alcaraz et al., 2000). The natural vegetation on slopes is mainly composed of Stipa tenacissima communities and dwarf-shrubs with Rosmarinus officinalis, Cistus clusii, Thymus membranaceus on mid and low areas. Harvesting of Stipa tenacissima tussocks was an important economic activity during the last centuries, which favoured its widespread occurrence in this part of Southeast Spain (Yanes, 1993). Slope vegetation at higher altitudes comprises Rhamno lycioidis-Quercetum cocciferae shrublands with Juniperus oxycedrus and Pistacia lentiscus, which is considered the climax vegetation in this semi-arid climate. On the Keuper formation, which is rich in
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gypsum, several endemic scrub species such as *Ononis tridentata*, *Salsola genistoides*, *Teucrium carolipau* and *Helianthemum squamatum* are common. Vegetation in channels and gullies is characterized by patches of riparian and salt tolerant semi-arid vegetation, with species such as *Nerium oleander*, *Tamarix canariensis*, *Brachypodium retusum*, *Juncus acutus* and reed beds of *Phragmites australis* (Navarro Cano, 2004). In reforested areas *Pinus halepensis* is the dominant species, followed by *Stipa tenacissima*, *Brachypodium retusum* and *Rosmarinus officinalis*, other species are insignificant in terms of cover.

Although this general vegetation description gives a short overview of the plant communities in the study area, the local conditions finally determine which vegetation species will occur. Especially slope exposure has a large effect on vegetation in semi-arid areas with high relief (Guerrero-Campo et al., 1999). North-facing slopes can sustain a higher vegetation cover and vegetation succession is faster due to lower evapotranspiration. On the northern slopes of the Sierra del Oro and Sierra de Almorchon a semi-natural forest is growing, while the southern slopes are mostly bare.

Plant community dynamics of Mediterranean basin ecosystems are mainly driven by an alternation of periods of human intervention and land abandonment. As a result, a mosaic of plant communities has evolved following different stages of degradation and regeneration (Gallego Fernández et al., 2004). Within the Carcavo basin abandoned fields with different stages of secondary vegetation succession are found. During the first years of abandonment the vegetation is dominated by annuals. Later dwarf shrub species and grasses become more important, *Artemisia herba-alba* and *Plantago albicans* are typical species for these stages of abandonment. The final stage of secondary vegetation succession is formed by *Rosmarinus officinalis* and *Stipa tenacissima* dominated communities. An ultimate successional stage of forest vegetation with *Quercus ilex* is not likely to occur under the semi-arid conditions of Southeast Spain, due to low water resources and intensive human disturbances over millennia (Rivas-Martínez, 1987).

1.5. Thesis outline

This thesis consists of seven chapters, of which this introductory chapter is the first one. Chapter 2 to 6 are based on scientific papers that have been published or have been submitted to peer reviewed international journals. In Chapter 2 vulnerable areas for gully erosion are identified under different scenarios of land abandonment for the Carcavo basin. A field survey revealed that abandoned land had more gully erosion compared to cultivated land. With a spatially explicit land use change model four scenarios with different rates of
land abandonment were simulated and potentially vulnerable areas for gully erosion were identified. Chapter 3 zooms in to the plot scale and describes the development of spatial heterogeneity in vegetation and soil properties after land abandonment. For two series of abandoned fields the vegetation succession, soil properties and vegetation patterns from detailed aerial photographs were analysed. Chapter 4 deals with a field scale study of the factors that increase erosion risk on abandoned fields. Since terrace failure was one of the major soil erosion processes on abandoned fields, we studied the causes of terrace failure in more detail. This chapter also discusses potential soil and water conservation practices for the mitigation of soil erosion after land abandonment. Chapter 5 describes the upscaling of fractional vegetation cover based on detailed aerial photographs and a QuickBird satellite image for the entire catchment. Different vegetation indices were evaluated for their suitability of upscaling fractional vegetation cover in a semi-arid environment. In Chapter 6 data and results from the previous chapters are integrated in a catchment scale runoff and erosion model. Vegetation patches at plot scale and agricultural terraces at hillslope scale were the most important sinks for runoff and sediment. The influences of these sinks were quantified and integrated in the infiltration module of the LAPSUS model to simulate the effect on the hydrological connectivity. Finally, a synthesis is given in Chapter 7, which summarises the main results in relation to the three central themes and discusses the implications of this thesis.