Assessment of morphodynamic processes and soil pollution as indicators of land degradation. A case study in the Tabernas area, southeastern Spain

Juan Fernando Palacio Pemberty
March, 2002
Assessment of morphodynamic processes and soil pollution as indicators of land degradation. A case study in the Tabernas area, southeastern Spain

by

Juan Fernando Palacio Pemberty

Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree in Master of Science in Earth Resources and Environmental Geosciences, Specialisation Geological Resource Management and Environmental Geology.

Degree Assessment Board

Thesis advisor Prof. Dr. Andrea G. Fabbri
Dr. Tsehaie Woldai
Dr. Luis Recatala Boix (CIDE)

Thesis examiners Prof. Dr. Salomon Kroonenberg (TU Delft)
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Abstract

Land degradation is a major environmental issue of global concern. It is defined as a process of deterioration of the fertile soils and loss of biological and economic productivity in different forms that leads to a situation of unbalanced environmental conditions. The semi-arid Mediterranean environments are one of the geographic areas affected by this type of process since historic times.

Two environmental indicators are proposed to study the land degradation that affects the Tabernas area in southeastern Spain: (i) the spatial distribution of morphodynamic processes through time, and (ii) the concentration of heavy metals to infer soil pollution. The study has been carried out using a geomorphological approach by the integration of multi-source and multi-temporal remotely sensed data (e.g., aerial photographs, Landsat and ASTER imagery), thematic information, field data collection and laboratory analysis using a geographic information system.

The influence of environmental components such as geology, geomorphology and human activities such as the changes in the land use and land cover patterns and asphaltisation in the development of geomorphic processes, and agricultural activities in the concentration of heavy metals was studied to preliminary define a Pressure–State–Response framework and tentatively infer future trends for the selected environmental indicators.

Keywords

land degradation, morphodynamic processes, soil pollution, environmental indicators, remote sensing, geographic information systems
Acknowledgements

Thanks once more to God for this new opportunity and wonderful experience in my life, for being always with me, for His presence that brings strength and calm to continue through the road.

I thanked the financial support offered by the Netherlands Fellowship Program and ITC that allowed me to explore a “small world” of new knowledge, skills and cultures. To INGEOMINAS and to the encouragement of my boss, colleagues and friends there.

My appreciation and sincere thankfulness to my advisors, Prof. Andrea G. Fabbri, Dr. Tsehaie Woldai and Dr. Luis Recatalá Boix; for your kindness, guidance, support, critical and constructive observations and advice throughout the development of the thesis.

To all the staff of the EREG program of ITC for their support in all this time. Special thanks to Dr. Ernst Schetselaar for the assistance during the fieldwork-s in Tabernas and his constructive “criticism”.

Thanks to Dr. Boudewijn de Smeth and Barbara Casentini for their guidance and assistance during the laboratory works.

Thank you Prof. Joseph Alfred Zinck for the revision of the manuscript and valuable comments.

Lots of great people I have met in this “small world” since September 13th, 2000. My deep gratefulness for your company all this time...it’s been and it is going to be hard to say “good bye”...my friendship will always be there my dear “amigos”.

Thanks to all my family, specially my grandma’ Rosa Margarita and my parents, Rosalba and Miguel, from whom I have received the most valuable advice ever, for their guidance through life, for their love and support in every single moment in life.

Thanks to the best friends, Claudia R., Val. and “los gusanos(as)”, they know who they are and what they mean to me.
3 Remote Sensing to Assess Land Degradation in Tabernas 21
  3.1 Introduction ............................................. 21
  3.2 Remotely Sensed Data Characteristics .......................... 21
    3.2.1 Aerial photographs ..................................... 22
    3.2.2 Landsat imagery ....................................... 23
    3.2.3 ASTER imagery ....................................... 23
  3.3 Image Processing .......................................... 25
    3.3.1 Radiometric correction ................................. 26
    3.3.2 Geometric corrections and image geo-referencing ......... 26
  3.4 Image Enhancement ......................................... 27
    3.4.1 Sum normalization ...................................... 27
    3.4.2 Principal component analysis ......................... 28
    3.4.3 Color composites ..................................... 29
  3.5 Image classification ....................................... 31
    3.5.1 Classification of sum-normalized Landsat images .......... 33
    3.5.2 Classification of VNIR ASTER bands ................... 37
    3.5.3 Additional comments on image classification .......... 37
  3.6 Conclusions ................................................. 42

4 Geomorphological Mapping to Assess Morphodynamic Processes as an Indicator of Land Degradation 44
  4.1 Introduction .............................................. 44
  4.2 Terrain Mapping Unit Approach ................................ 44
  4.3 Description of the Geomorphologic Units in the Study Area ...... 45
    4.3.1 Geomorphologic units of the basement mountains .......... 47
    4.3.2 Geomorphologic units of the Neogene sedimentary and Quaternary cover ........................................ 49
  4.4 Geomorphologic Processes and Associated Landforms ............ 55
    4.4.1 Morphodynamic processes in 1956 ........................ 58
    4.4.2 Morphodynamic processes in 1981 ........................ 59
    4.4.3 Morphodynamic processes in 1995 ........................ 61
  4.5 Conclusions ............................................... 63

5 Morphodynamic processes, Geomorphology and their Relationships with Natural Components of the Environment and Human Activities 64
  5.1 Introduction .............................................. 64
  5.2 Morphodynamic Processes and their Relationships with Natural Components of the Environment .................. 65
    5.2.1 Morphodynamic processes and geology .................. 65
    5.2.2 Morphodynamic processes and geomorphology ........... 66
  5.3 Morphodynamic Processes and their relationships with human activities ............................................. 68
    5.3.1 Morphodynamic processes and changes in land use ........ 69
    5.3.2 Morphodynamic processes and changes in land cover ...... 72
    5.3.3 Morphodynamic processes and asphaltisation .......... 76
  5.4 Geomorphology and its relationships with human activities .... 82
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4.1 Geomorphology and changes in land use between 1956 and 1995</td>
<td>83</td>
</tr>
<tr>
<td>5.4.2 Geomorphology and changes in land cover between 1956 and 1995</td>
<td>84</td>
</tr>
<tr>
<td>5.5 Conclusions</td>
<td>85</td>
</tr>
<tr>
<td>6 Preliminary Assessment of Soil Pollution as an Indicator of Land Degradation</td>
<td>87</td>
</tr>
<tr>
<td>6.1 Introduction</td>
<td>87</td>
</tr>
<tr>
<td>6.2 Distribution of heavy metals in the soils</td>
<td>87</td>
</tr>
<tr>
<td>6.3 Methods and Techniques</td>
<td>89</td>
</tr>
<tr>
<td>6.3.1 Soil sampling procedures</td>
<td>89</td>
</tr>
<tr>
<td>6.3.2 Laboratory analyses</td>
<td>91</td>
</tr>
<tr>
<td>6.4 Evaluation of the Results</td>
<td>101</td>
</tr>
<tr>
<td>6.4.1 Inter-element correlation</td>
<td>103</td>
</tr>
<tr>
<td>6.5 Soils and Human Activities</td>
<td>107</td>
</tr>
<tr>
<td>6.6 Conclusions</td>
<td>108</td>
</tr>
<tr>
<td>7 Discussion and Evaluation of the Results</td>
<td>110</td>
</tr>
<tr>
<td>7.1 Introduction</td>
<td>110</td>
</tr>
<tr>
<td>7.2 A First Approach to develop Indicators of Land Degradation in the Tabernas Study Area</td>
<td>110</td>
</tr>
<tr>
<td>7.2.1 Causes and effects in the development of the morphodynamic processes</td>
<td>112</td>
</tr>
<tr>
<td>7.3 A Preliminary Analysis for the Indicators of Land Degradation in a Pressure–State–Response Framework</td>
<td>115</td>
</tr>
<tr>
<td>7.3.1 Extent of the area affected by morphodynamic processes in a PSR framework</td>
<td>115</td>
</tr>
<tr>
<td>7.3.2 Concentration of heavy metals in the soils in a PSR framework</td>
<td>116</td>
</tr>
<tr>
<td>7.4 Is it Possible to Infer Future Trends in Land Degradation?</td>
<td>117</td>
</tr>
<tr>
<td>7.5 Potentials and Limitations of the Remotely Sensed Data to Support the Geomorphologic Mapping</td>
<td>119</td>
</tr>
<tr>
<td>7.6 Potentials and Limitations of the Study</td>
<td>121</td>
</tr>
<tr>
<td>7.7 Potentials of the study</td>
<td>121</td>
</tr>
<tr>
<td>7.8 Limitations of the study</td>
<td>122</td>
</tr>
<tr>
<td>8 Conclusions and Recommendations</td>
<td>123</td>
</tr>
<tr>
<td>8.1 Conclusions</td>
<td>123</td>
</tr>
<tr>
<td>8.2 Recommendations</td>
<td>124</td>
</tr>
<tr>
<td>References</td>
<td>126</td>
</tr>
<tr>
<td>Appendix 1</td>
<td>132</td>
</tr>
</tbody>
</table>
# List of Figures

1.1 Operational flowchart ................................................. 6

2.1 Location of the study area ........................................... 10

2.2 Geologic map of the Tabernas study area. Source [34], and [2] .... 13

2.3 Land use classes and their changes from 1956 to 1995 in the Tabernas area.......................................................... 18

2.4 Land cover classes and their changes from 1956 to 1995 in the Tabernas area.......................................................... 18

2.5 Road construction in the Tabernas area from the 50s to the year 2000. 20

3.1 Color composite of sum normalized Landsat image, Bands 451 in RGB, respectively .......................................................... 30

3.2 Color composite of sum normalized Landsat image, Bands 451 in RGB, respectively .......................................................... 31

3.3 False color composite of ASTER Bands 321 in RGB, respectively . 32

3.4 Classified Landsat bands 4,5,1 in RGB, respectively ................. 34

3.5 Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite obtained from the combination of bands 4,5,1 in RGB, respectively, of sum normalized Landsat image. .................................................. 34

3.6 Feature spaces of classified Landsat sum-normalized bands 4,5,1 . 35

3.7 Classified image generated by the color composite of principal components 1,2,3 in RGB of sum normalized Landsat image. .................................................. 36

3.8 Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite obtained from the principal components 123 in RGB, respectively, of sum normalized Landsat image bands. .................................................. 36

3.9 Feature spaces of classified principal components 123 of sum normalized Landsat image. .................................................. 37

3.10 Classified ASTER image ................................................... 38

3.11 Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite created from ASTER bands 321 in RGB, respectively . .................................................. 38

3.12 Feature spaces of classified ASTER image ................................ 39

3.13 Insets of classified Landsat and ASTER images. ....................... 41

3.14 Insets of classified Landsat and ASTER images. ....................... 42
4.1 Map of geomorphologic units of the Tabernas area. .................. 46
4.2 Panoramic view of the Sierra de Los Filabres (at the background), with strong structural control visible in the water divider shape and orientation. Limestone hills in the middle of the photograph are surrounded by an undulating relief of recent deposits. .................. 47
4.3 Areas of steep relief (scarps in marbles) in the Sierra Alhamilla in the vicinity of Lucainena de las Torres, at the bottom a lower relief in Tertiary sediments. ............................ 49
4.4 Rills developed in phyllites in the Sierra Alhamilla near Lucainena de Las Torres. .................................................. 50
4.5 View of the ‘Serrata del Marchante” and of the areas of undulating relief showing a contrasting morphology. .................. 50
4.6 Panoramic view of the badlands of Tabernas, the strong morphodynamic activity and the characteristic morphology are distinctive features of this unit. ............................ 52
4.7 Three different levels of peneplanation surfaces can be recognized in the photograph, at the background is the geomorphologic unit “Moderate Relief of Sierra Alhamilla” ............................ 54
4.8 Areas of sheet erosion in the foothills of the Sierra Alhamilla. .......... 56
4.9 Gullies developed in soft marls in the Tabernas badlands area. ........ 57
4.10 Morphodynamic processes in the year 1956. .................. 59
4.11 Extent of morphodynamic processes in the year 1956. ................ 60
4.12 Morphodynamic processes in the year 1981. .................. 60
4.13 Extent of morphodynamic processes in the year 1981. ................ 61
4.15 Extent of morphodynamic processes in the year 1995. ................ 62
5.1 Areas with land use changes from 1956 to 1981 that have been affected by morphodynamic processes. .................. 70
5.2 Areas of land use changes between 1956 and 1981. The squares represent areas that coincide with morphodynamic processes. Source of land use change map [2] .................. 71
5.3 Areas with land use changes from 1981 to 1995 that have been affected by morphodynamic processes. .................. 72
5.5 Areas with land cover changes from 1956 to 1981 that have been affected by morphodynamic processes. .................. 74
5.6 Areas of land cover changes between 1956 and 1981. The rectangular forms represent areas that overlay with morphodynamic processes. Source of the land use change map [2]. .................. 75
5.7 Areas with land cover changes from 1981 to 1995 that have been affected by morphodynamic processes. .................. 76
5.8 Areas of land cover changes between 1956 and 1981. The rectangular forms represent areas that overlay with morphodynamic processes. Source of land cover change map [2]. .................. 77
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Road distribution in 1950 overlaid with morphodynamic processes in 1956. The enclosed areas with rectangular forms represent affected areas of the different road classes. Source of road map [2].</td>
<td>78</td>
</tr>
<tr>
<td>5.10</td>
<td>Areas of the different road classes affected by morphodynamic processes in the 50s.</td>
<td>78</td>
</tr>
<tr>
<td>5.11</td>
<td>Road distribution in 1985 overlaid with morphodynamic processes in 1981. The enclosed areas with rectangular forms represent affected areas of the different road classes. Source of road map [2].</td>
<td>79</td>
</tr>
<tr>
<td>5.12</td>
<td>Areas of the different road classes affected by morphodynamic processes in the 80s.</td>
<td>80</td>
</tr>
<tr>
<td>5.13</td>
<td>Road distribution in 2000 overlaid with morphodynamic processes in 1995. The enclosed areas represent the overlap between the road classes and the processes. Source of road map [2].</td>
<td>81</td>
</tr>
<tr>
<td>5.14</td>
<td>Areas of constructed roads in 2000, affected by morphodynamic processes.</td>
<td>82</td>
</tr>
<tr>
<td>5.15</td>
<td>Extent of geomorphologic units affected with land use changes between 1956 and 1995.</td>
<td>84</td>
</tr>
<tr>
<td>5.16</td>
<td>Extent of geomorphologic units affected with land cover changes between 1956 and 1995.</td>
<td>85</td>
</tr>
<tr>
<td>6.1</td>
<td>Soil sampling sites and land uses associated. Source of land use map [2].</td>
<td>90</td>
</tr>
<tr>
<td>6.2</td>
<td>Database structure generated to store and manage the soils information.</td>
<td>92</td>
</tr>
<tr>
<td>6.3</td>
<td>Flow chart of the procedure to determine the total metal concentration [16].</td>
<td>93</td>
</tr>
<tr>
<td>6.4</td>
<td>Flow chart of the procedure to determine the extractable metals concentration [16].</td>
<td>96</td>
</tr>
<tr>
<td>6.5</td>
<td>Scatterplots of total concentrations of elements with the highest correlation coefficients.</td>
<td>104</td>
</tr>
<tr>
<td>6.6</td>
<td>Scatterplots of extractable concentrations of elements with the highest correlation coefficients.</td>
<td>105</td>
</tr>
<tr>
<td>7.1</td>
<td>Pressure–State–Response framework, from [54].</td>
<td>116</td>
</tr>
<tr>
<td>7.2</td>
<td>Indicative trends for geomorphologic processes in the Tabernas study area</td>
<td>118</td>
</tr>
</tbody>
</table>
## List of Tables

2.1 Land use classes and their extension in the Tabernas area. Taken from [2]. .......................................................... 15
2.2 Land cover classes and their extension in the Tabernas area. Taken from [2]. .......................................................... 16
2.3 Road construction in the Tabernas area from the 50s to the year 2000 (adapted from [2]). ........................................... 19
3.1 Remotely sensed data characteristics. .............................................. 25
3.2 Correlation matrix of non normalized Landsat image, bands 1 to 7 (B1...B7). .......................................................... 27
3.3 Correlation matrix of sum normalized Landsat image, bands 1 to 7 (B1...B7). .......................................................... 28
3.4 Principal components of sum normalized Landsat image, bands 1 to 7 (B1...B7). .......................................................... 28
3.5 Confusion matrix of the classified sum normalized Landsat image, bands 4,5,1. .......................................................... 39
3.6 Confusion matrix of the classified sum normalized Landsat image, principal components 1,2,3. ........................................ 40
3.7 Confusion matrix of the classified false color composite ASTER image, bands 3,2,1. .......................................................... 40
5.1 Area of morphodynamic processes in 1956 affecting the geologic formations in the Tabernas area. ........................................ 65
5.2 Area of morphodynamic processes in 1995 affecting the geologic formations in the Tabernas area. ........................................ 66
5.3 Area of morphodynamic processes in 1956 affecting the geomorphologic units in the Tabernas area. ........................................ 67
5.4 Area of morphodynamic processes in 1981 affecting the geomorphologic units in the Tabernas area. ........................................ 67
5.5 Area of morphodynamic processes in 1995 affecting the geomorphologic units in the Tabernas area. ........................................ 68
5.6 Areas with land use changes from 1956 to 1981 that have been affected by morphodynamic processes. ........................................ 69
5.7 Areas with land use changes from 1981 to 1995 that have been affected by morphodynamic processes. ........................................ 70
5.8 Areas with land cover changes from 1956 to 1981 that have been affected by morphodynamic processes. ........................................ 72
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Areas with land cover changes from 1981 to 1995 that have been affected by morphodynamic processes.</td>
<td>75</td>
</tr>
<tr>
<td>5.10</td>
<td>Areas of the different road classes affected by morphodynamic processes in the 50s.</td>
<td>77</td>
</tr>
<tr>
<td>5.11</td>
<td>Areas of the different road classes affected by morphodynamic processes in the 80s.</td>
<td>79</td>
</tr>
<tr>
<td>5.12</td>
<td>Areas of constructed roads in 2000, affected by morphodynamic processes.</td>
<td>81</td>
</tr>
<tr>
<td>5.13</td>
<td>Areas of geomorphologic units where land use changes have taken place between 1956 and 1995.</td>
<td>83</td>
</tr>
<tr>
<td>5.14</td>
<td>Areas of geomorphologic units where land cover changes have taken place between 1956 and 1981.</td>
<td>84</td>
</tr>
<tr>
<td>6.1</td>
<td>Total metal in soil samples from the Tabernas study area. The concentrations are in (%) for Fe and ppm for the rest of elements. For Cd, the obtained values were reported below 0.1 ppm.</td>
<td>94</td>
</tr>
<tr>
<td>6.2</td>
<td>Standard values for total metal concentrations (ppm) in soils presented by [39] and maximum values obtained for the Tabernas soils.</td>
<td>95</td>
</tr>
<tr>
<td>6.3</td>
<td>Concentrations in (ppm) of extractable (Extr) and percentage of the total metals (%Tot.) in soil samples from the Tabernas study area.</td>
<td>97</td>
</tr>
<tr>
<td>6.4</td>
<td>Results and statistics for the determination of pH and Ec (in dS/m).</td>
<td>98</td>
</tr>
<tr>
<td>6.5</td>
<td>Concentrations (in ppm) of the exchangeable cations measured to calculate CEC. It can be observed the high values for Ca, Na and Mg in some samples.</td>
<td>100</td>
</tr>
<tr>
<td>6.6</td>
<td>Results and statistics obtained for particle size, organic carbon and organic matter content.</td>
<td>101</td>
</tr>
<tr>
<td>6.7</td>
<td>Background and reference concentration levels in (ppm) for heavy metals in soils from Cataluña, The Netherlands, United Kingdom and Canada ([36] and [3]).</td>
<td>102</td>
</tr>
<tr>
<td>6.8</td>
<td>Correlation matrix for total metals.</td>
<td>104</td>
</tr>
<tr>
<td>6.9</td>
<td>Correlation matrix for the extractable metals.</td>
<td>105</td>
</tr>
<tr>
<td>6.10</td>
<td>Correlation coefficients between total and extractable metal concentrations for the analyzed metals.</td>
<td>106</td>
</tr>
<tr>
<td>6.11</td>
<td>Correlation coefficients between total metals (upper portion), extractable metals (lower portion) and organic matter and clay fraction.</td>
<td>106</td>
</tr>
<tr>
<td>6.12</td>
<td>Associated land use class for analyzed samples. Concentration for total (T) and extractable (E) heavy metals in (ppm) and in (%) for total Fe.</td>
<td>108</td>
</tr>
<tr>
<td>7.1</td>
<td>Extent of morphodynamic processes between 1956 and 1995 in the Tabernas study area.</td>
<td>114</td>
</tr>
<tr>
<td>7.2</td>
<td>Indicative trends for geomorphologic processes in the Tabernas study area.</td>
<td>118</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Land degradation is a process of deterioration of the fertile soils and loss of biological and economic productivity in different forms that leads to a situation of unbalanced environmental conditions. Even though the process of land degradation can be due to the intrinsic environmental characteristics of the natural environment, the human influence through unplanned and irrational exploitation of the earth resources can accelerate and aggravate the development of this process.

Land degradation is a major environmental problem of concern in the world. The semi-arid Mediterranean environments are one of the geographic areas affected by this type of process and their causes and extent have been the object of study for more than one decade. The term “desertification”, has been interpreted as land degradation in arid, semi-arid and dry-humid environments and the first worldwide attempts to deal and combat it come from the United Nations Conference on Desertification organized by UNEP, which was held in Nairobi, Kenya in 1977.

The application and integration of multi-sources of information represent a major goal to achieve more satisfactory results in the assessment of many environmental issues. The use of new technologies and science developments such as remote sensing, geographic information systems, field data collection, database development and laboratory experiments have made it possible to approach the study of land degradation from a multidisciplinary perspective.

The actions of planning and managing the use of natural resources are of primary importance nowadays to integrate and focus the generation of geo-information to develop or improve the policies for a sustainable development. To achieve this, in the case of the semi-arid Mediterranean environments, the requirements of comprehensive and accurate information about the spatial distribution and dynamics of land degradation processes is one of the priorities of special interest in order to formulate the policies for an integrated environmental planning.

The increasing human interference with the natural environment, due to economic and social pressures, has resulted in inadequate land management, intensive changes in recent years of the land use and land cover patterns, mining and quarrying, soil pollution and soil compaction. Those practices, besides the natural setting and environmental characteristics of the Mediterranean region, specially in south-east Spain; resulted as the major contributors to the development of the land degradation processes throughout the history.
1.1. Review of Land Degradation in Mediterranean Environments

The area located in the “comarca” of Tabernas, which belongs to the province of Almería in south-east Spain, was selected to conduct the assessment of two indicators of land degradation: The spatial distribution of erosional features through time and the actual state of heavy metals content and other soil properties that permit to infer soil pollution. The approach that will be followed to assess those indicators is based on the collection and analysis of secondary, as well as field information. It also involves the use of remote sensing, geographic information systems and laboratory techniques.

1.1 Review of Land Degradation in Mediterranean Environments

The terms land degradation and desertification have a close relationship and several attempts to define and describe them have been made [68], [17], [46]. Desertification was redefined by [68] in the sense of considering it as “the land degradation in arid, semiarid and dry-semi-humid areas resulting mainly from adverse human impact”. The term land includes land and local water resources, the land surface and its natural vegetation. It is important to notice that this definition, attributes the causes of land degradation to natural processes and human activities are introduced as another factor.

Land degradation can be defined from another perspective, [17], as “alterations to all aspects of the natural (or biophysical) environment by human actions, to the detriment of vegetation, soils, landforms, water (surface and subsurface) and ecosystems”. In this definition, the natural conditions of the area are not considered as factors that can threaten land degradation and the human activities are the main responsible factors for the development of this phenomenon.

According to [59], desertification affects all dry land zones over the five continents. Almost 900 million people suffer currently the consequences of desertification in the world, and over 5 billion ha (equal to one quarter of the emerged land) are affected by these processes. In total, 98 countries (including 18 developed countries) have some land area affected by desertification.

The problem of land degradation in the world was studied initially at a world scale by an initiative of the United Nations Environmental Program (UNEP) and the International Soil Reference and Information Center (ISRIC). The study was developed from a soil resource perspective and as a human-induced phenomenon. The project was entitled: Global Assessment of Soil Degradation (GLASOD) and the objective was to produce a 1:10 M world map on the status of human-induced soil degradation [46].

In Europe, desertification processes affect approximately 10% of the total area. The Mediterranean and Eastern European Regions are specially threatened by desertification due to natural and economic pressures, which are the main causes for the intensification of the process [59]. The history of land degradation in the Mediterranean region is very long and it has been extensively studied in many countries.

1“comarca” is a term that defines a territorial entity in Spain that groups some municipalities.
1.2 Background of the research

Several are the factors that can result in land degradation and desertification. The more important ones are unsustainable human activities and climatic variability. Related to the former in the European Mediterranean environments, the accelerated development (specially in the last decades), brings activities such as agricultural intensification, industrial and urban expansion and infrastructure, extensive deforestation, overgrazing, man induced fires and inadequate soil management practices that threatened and increases the risk to land degradation and desertification [59].

From a historical perspective of land degradation, agricultural practices of 750 or even 1500 BC and earlier involved enormous geo-ecological impacts as water table were lowered by irrigation works, and grazing was improved by man fires [33]. In the same publication, the author remarks how important it is to develop indicators that can be used at different spatial and temporal domains and scales, and more important, is the fact that they must be based on soil or land–resource functions in order to identify areas that are losing valued ecological functions as a result of desertification at the present time.

Several integrated and complementary field investigations of desertification have been started in southern Europe as part of large European Commission research programmes (EPOCH, ENVIRONMENT and ENVIRONMENT & CLIMATE) [32]. That commission, has established through its Environment Programme an investigation to identify, understand and mitigate the effects of desertification in southern Europe. Mediterranean Desertification and Land Use (MEDALUS) is the largest project in this programme. Its first phase was initiated in January 1991 and currently it is in its third phase, which was initiated in December 1998 and involves 31 groups of work in ten countries.

In an integrated view of desertification, MEDALUS includes field studies of soil erosion and vegetation growth, climate variability and climatic change, computer modelling of river basin response to change, and socioeconomic issues related to land degradation processes. Also, an important component is the identification of possible mechanisms for mitigating land degradation effects in the context of Mediterranean Europe (http://www.medalus.demon.co.uk/ outline. html).

The Satellite Based Desertification Monitoring in the Mediterranean Basin, DeMon project (phases I and II), has been another effort to contribute to the assessment of land degradation in the Mediterranean environments. The use of remotely sensed data, GIS and computer simulation has been extensively applied in different pilots areas in Spain, France and Crete. The first phase, DeMon-1 (1992-1995), was focussed on the experimental development of monitoring and modelling methods. The second phase, DeMon-2 (1996-1999) aimed at refining the earlier developed methods (http://www.frw.ruu.nl /fg/demon.html).

1.2 Background of the research

A region located in the “comarca” of Tabernas, south-east Spain, was selected as a pilot area for the project entitled “Euro-Latin American Network for Environmental Assessment and Monitoring, ELANEM”, in which the Geological Survey Division
of the International Institute for Geo-information Science and Earth Observation (ITC), and the Centro de Investigaciones sobre Desertificación (CIDE), are together one of the ten partners around Europe and Latin America. The project started on May 1999 and is to end in May 2002. The main objective of the project is to develop and test a methodology to measure the environmental quality based on the identification, assessment and combination of quantitative indicators and indices (http://www.citimac.unican.es/ELANEM/portada.html).

The ELANEM project partners have suggested an indicator based approach methodology [13], and a Pressure–State–Response framework [45], [50], [61] to achieve the goal of evaluating the environmental quality in the different pilot areas. They are based on the identification and assessment of a series of environmental indicators that permit to measure the pressures exerted, the state of and the policies for managing the environment and its natural resources. Environmental functions like degree of naturalness, support of services and sink of wastes are evaluated through specific indicators. The role of remote sensing and geographic information systems as well as field data collection and laboratory analysis has been relevant to their construction and evaluation.

As part of the evaluation of the environmental quality of the Tabernas area, previous works have been carried out under the ELANEM project. Aspects such as land use, land cover and their changes through the last 50 years [2], definition of environmental units [54], evaluation of the degree of naturalness [53], soil moisture measurements and desert-like features mapping [41] have been studied. In each of these works only one specific type of remotely sensed data has been employed (or aerial photographs or hyperspectral imagery or satellite imagery). The capabilities and limitations of different and more recent type of sensors, as well as possibilities of data integration have not yet been explored.

The aspects that have been investigated in the previous works are related to a certain extent to the land degradation problem that affects the area of Tabernas. The intrinsic environmental conditions and characteristics (geology, climate, soils, morphodynamic processes, vegetation) and the human interference with the natural environment have resulted in: inadequate land management, intensive changes in recent years of the land use and land cover, mining and quarrying, soil contamination and soil compaction, over-pumping of groundwater and overgrazing. These are the main aspects that have to be understood and mapped in order to evaluate the state and probably infer the future trends of the land degradation process.

1.3 Objectives

1.3.1 General Objective

The main objective is to identify and characterize two indicators of land degradation, such as, (i) the spatial distribution of morphodynamic processes and (ii) the concentration of heavy metals to infer soil pollution. The work has been carried out using a geomorphological approach by the integration of multi-source and multi-temporal remotely sensed data, field data collection and laboratory analysis using a
1.3.2 Specific Objectives

- To map the extent of erosional features during the past 50 years as an indicator of land degradation.

- To conduct a preliminary assessment of soil pollution by analyzing the heavy metals content and other chemical and physical properties in soil samples.

- To apply methods of multi-source and multi-temporal data integration to evaluate the nature and extent of land degradation indicators and infer future trends of these processes.

- To identify and evaluate human activities such as changes in land use, land cover and asphaltisation; and their relationship with the land degradation indicators proposed.

- To evaluate the potentials and limitations of remotely sensed data e.g., aerial photographs, Landsat and ASTER imagery to map erosional features and processes.

1.4 Importance of the Research

The assessment of erosional features and processes and soil pollution as indicators of land degradation in the area of Tabernas, represents a contribution to understand the dynamics of the natural environment as well as the pressures exerted by human activities.

The relationships that can be established regarding the dynamic of natural processes under the intervention of human activities are the basis to identify future trends in land degradation.

The integration of multi-temporal and multi-sources of information as well as remotely sensed data of different resolution constitutes a significant advance to detect, map and monitor natural environments under the influence of human activities.

1.5 General Methodology

This section describes the operational workflow that will be followed during the development of this research. Particular details about the satellite imagery processing aspects, geomorphological and morphodynamic processes mapping approaches, as well as soil data collection, sampling procedures, sample preparation and laboratory analysis; will be presented in separate chapters. A flow chart of the operational aspects is presented in (Figure 1.1).

Traditional approaches to the assessment of land degradation usually involve the production of maps showing the extent and intensity of morphodynamic processes such as sheet or gully erosion, analysis of vegetation characteristics and land cover...
1.5. General Methodology

Figure 1.1: Operational flowchart
1.5. General Methodology

and land use distribution. Commonly, they are based on the use of aerial photographs, and the results are subjective and sometimes can overestimate the extent of degradation [49]. To overcome those problems, the use of satellite remote sensing techniques has been an alternative approach and has increased in recent years. Spectral contrast between bare soil and vegetation or between different levels of vegetation cover at the scale of whole landscapes can be used to develop surrogate measures of degradation [28] and [49].

To accomplish the formulated objectives, the first step was a literature review on the main aspects of land degradation and the use of remotely sensed data for its study. Then, an extensive review of the previous studies and works carried out in the Tabernas area was made to identify sources of secondary information. After this, traditional and satellite remote sensing techniques, followed by a stage of field data collection, processing and analysis was combined as a support to characterize, evaluate and map (when it applies); the two indicators of land degradation selected for this study.

Regarding the geomorphological and morphodynamic mapping process, a stage based on image processing techniques (Chapter 3), including the geometric and radiometric correction of satellite imagery, filtering and stretching was conducted to obtain enhanced products to be used for visual as well as digital image interpretation and analysis. Classified Landsat and ASTER images were obtained where land cover features, related to land degradation were extracted. A terrain mapping unit approach is described in Chapter 4, where feature extraction from a digital elevation model was carried out to support the geomorphological mapping process. Several thematic maps were obtained from this phase such as: a map of geomorphologic units, a map showing spatial distribution of morphodynamic processes during 1956, 1981 and 1995; and slope inclination, shape and aspect maps.

In Chapter 5, the use of GIS overlay operations, like “map cross”, permitted to establish the relationships between the morphodynamic processes, natural components of the environment and human activities. To accomplish this, thematic maps of changes through time in land use and land cover, geomorphologic and lithologic units, land use and land cover classes as well as the maps that represent the road construction and development in the Tabernas area, were crossed with the morphodynamic maps for different periods of time. This permitted to infer their susceptibility to present certain type of morphodynamic process and statistical information of areal extent of morphodynamic processes in different thematic units was derived and compared to infer trends in time for their distribution.

The preliminary analysis of heavy metal contents in soil samples to assess the state of soils and detect pollution levels is another component of this research that is described in Chapter 6. To conduct the analysis, a procedure for the selection of random sampling sites was carried out. The criteria used to establish the sites was morphological (piedmont and valley areas) and land use (cultivated areas). A relational database was generated to facilitate the storage and management of the data collected in the field, as well as the laboratory analyses.

Soil analyses were conducted at the geochemical laboratory of ITC over the 21 samples collected in the field. Determination of total and extractable metals, pH, electrical conductivity, particle size, organic matter content and cationic exchange capability were the main properties and analysis carried out. The samples were
1.6 Data available

In order to develop the research, information that was generated in recent works [2], [41] was used as basic support to produce the different cartographic products. It includes digital remotely sensed data as well as ancillary information.

The use of internet was very important to obtain relevant information such as “free of charge” images captured by the Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER), reports from previous projects on desertification in Mediterranean environments, like MEDALUS and DeMon; and data produced by the “Junta de Andalucía” (the Environmental Corporation with jurisdiction in the study area).

1.6.1 Remotely sensed data

In this subsection, a list of the remotely sensed data used in this research is presented. A general description of each particular sensor and images acquired for this investigation will be presented in Chapter 3.

- A LANDSAT5 image acquired in January 29th, 1986.
- ASTER imagery acquired in July 14th, 2000.

1.6.2 Ancillary data

- Analog 1:50,000 topographic map [62].
- Analog 1:50,000 geological map [34].
- Analog 1:100,000 soil map [43].
- Analog 1:50,000 environmental units map [53].
- Digital geological 1:50,000 and soil 1:100,000 maps [2].
- Digital 1:50,000 land use, land cover maps and the changes detected for the years 1956, 1981 and 1995 [2].
- Digital elevation model (DEM) with 25 mt resolution.
- Publications, technical reports and theses completed for the study area.
Chapter 2

Description of the Study Area

2.1 Location and access

The study area is located 30 km north of the city of Almería in south-east Spain as shown in Figure 2.1. The natural boundaries are the northwestern flank of the Sierra Alhamilla at the south, and the Sierra de Los Filabres towards the north. The area covers an extension of nearly 300 km$^2$, and the coordinate boundaries in the UTM zone 30S obtained from the topographical map Series M7814, sheet (23-42) [62] are: $X_1$:543000, $Y_1$:4095000 and $X_2$:572000, $Y_2$:4113000.

The city of Almería belongs to the province with the same name which is part of the Region of Andalucía. The town of Tabernas is the largest municipality in the study area and covers its central portion. It is located at 400 m.a.s.l and has 3,500 inhabitants. The surrounding municipalities are: Turrillas, Lucainena de las Torres, Nijar, Uleila del campo, Tahal, Senés, Velefique, Castro de Filabres, Olula de Castro, Gérgal, Gador, Santa Fe de Modújar and Rioja.

The study area in general has good communication roads. The main access from Almería is the national road CN-340 in direction to Murcia. Secondary roads connect the mentioned municipalities and are in good conditions throughout the year. The “Rambla de Tabernas” as well as some other “ramblas” act as natural communication roads. The low and scarce vegetation permits an easy access to every place in the area.

2.2 Climate

The climate of the area is thermo-Mediterranean semi-arid. It has a mean annual precipitation of 248 mm, according to a 25-year recording period station in Tabernas. Annual precipitation ranges from 115 to 431 mm. The number of rainy days varying from 25 to 55 with an average number of rainy days is 37 [64]. They are concentrated in two periods, spring and fall. The maximum rainfalls are produced in October and December.

The mean annual temperature in Tabernas is 17.9°C, with an average minimum of 4.1°C in the coldest month and an average of 34°C in the hottest month. Daily amplitudes average 13.7°C during summer [64].
The topographic conditions play an important role in the climatic characteristics of the Tabernas study area. The mountains of the Sierras Alhamilla and Los Filabres constitute natural barriers for the winds and humid conditions that come from the Mediterranean Sea. An east–west corridor formed by low areas where most of the study area is located presents special characteristics that define micro-climatic conditions of aridity.

In response to the interest in problems of aridity and desertification, a map showing the world distribution of deserts was produced in 1977 [67]. For this map, arid regions were delimited partly on the basis of aridity indices and partly from considerations of all available data on soil, relief and vegetation. The degree of bio-climatic aridity was defined by the ratio of the mean annual precipitation $P$ to the mean annual potential evapotranspiration $E_{TP}$ [1]. Four main classes of aridity were defined by [67]:

- The hyperarid zone ($P/E_{TP} > 0.03$)
- The arid zone ($0.03 < P/E_{TP} < 0.20$)
- The semi-arid zone ($0.20 < P/E_{TP} < 0.50$)
- The subhumid zone ($0.50 < P/E_{TP} < 0.75$)

In the study area, the mean annual precipitation value is 248 mm and the mean potential evapotranspiration $E_{TP}$ 779.5 mm [70]. Then, the ratio ($P/E_{TP}$) is about 0.314 which corresponds according to the classification of [1] to a semi-arid zone. Other climatic classifications [66] in [53] identifies the area as an arid zone.

It is important to define the climatic setting of the study area because it is one of the factors that controls the soil and landscape development as well as the dynamic
of the geomorphologic processes through time. The semi-arid conditions that governs
the climate in the Tabernas area, as well as tectonic uplift have exerted a strong
control in badlands development through several stages in a context of sequential
dry climates [56] in [64].

2.3 Physiography

The morphostructural divisions permit to distinguish broad physiographic complexes
with common evolutive characteristics. These characteristics refer basically to geo-
logic evolution (lithology and structure). Then, the morphostructural complexes are
the result of the action of endogenous processes through time, that are represented
in this case by tectonic activity. The climatic conditions are also important in terms
of modelling the landscape in a more restricted temporal scale.

In a general sense, the limits between different morphostructural complexes coin-
cide with broad geologic units. When a more detailed differentiation is proposed, this
limit no longer match with the geological boundaries and geomorphologic, morphoge-
netic and climatic criteria are the parameters that play an important role to delineate
the extent and limits of different units.

The Iberian Peninsula is located in the southeastern part of the European conti-
inent. The relief is mainly mountainous with an average height of about 660 m. Ex-
tensive peneplain surfaces (located mainly in the central side) and low lands corres-
ponding to Tertiary basins and Quaternary deposits are developed and often linear
contacts separate this basins from the mountain areas. In a broad sense, four morp-
hostructural complexes can be differentiated in the Iberian Peninsula [24], are:

- The Western Hercininan Complex
- The Betic Cordilleras
- The Pirenaic Cordilleras
- The Internal Basins (Ebro, Tajo and Duero depressions).

The study area is located in the Betic Cordilleras, which are formed by mountai-
nous areas that can be followed in the southern part of Spain for almost 600 km [24].
Two morphostructural units defined by [54], [53] and [2] will be presented to explain
the most relevant aspects of the physiography of the Tabernas area. They are, Base-
ment Mountains and Neogene Sedimentary Basin and Quaternary Deposits. Each of
them have lithologic and morphometric characteristics that permits this differentia-
tion as will be introduced in Chapter 4. Besides, in terms of climatic and ecological
setting, these two zones present substantial differences.

- **Basement Mountains**: They Comprise the higher lands of the area, which
corresponds to the Sierras de Los Filabres and Alhamilla where the metamorp-
hic complexes of Malaguide, Alpujarride and Nevado Filabride that will be des-
cribed in Section 2.4 outcrop.
2.4 Geology

- **Neogene Sedimentary Basin and Quaternary Deposits**: Correspond to the hilly and flat lowlands. They are formed by consolidated sedimentary rocks of marine and continental environment of deposition and unconsolidated fluvial deposits.

The physiographic aspects in the study area, present a strong influence in other related natural environmental components e.g. geology; as well as human activities e.g. land cover and land use. The terrain morphology in most cases, limits and favours the development of agricultural activities. Detected changes in the land use and land cover patterns are related in a great extent to certain geomorphologic units as will be presented in Chapter 5.

### 2.4 Geology

The geological aspects of the study area have been extensively studied by a variety of scientists and research groups from different universities and institutions in Europe [34], [52], [4], [76], among others. The geology of Tabernas is framed in the Betic Cordilleras as was described in Section 2.3. The rocks that outcrop in these areas were formed by the interaction of the European and African plates in Late Mesozoic and Early Tertiary times [52] and can be divided according lithologic, tectonic and paleogeographic criteria in:

- **The External Zone**: It is formed at the passive continental margins of South and East of the Iberian Massif. The External Zone is subdivided in to a pre-Betic and sub-Betic districts, comprising non-metamorphic sedimentary rocks of essentially Mesozoic and Tertiary age [76].

- **The Internal or Betic Zone**: It consists of a stack of four nappe complexes that can be differentiated based on the tectonic and metamorphic evolution [4]. From the highest structural levels downwards they can be distinguished in: The *Malaguide Complex*, *Alpujarride Complex*, *Veleta and Mulhacen Complexes*; the last two conforms what traditionally has been named the *Nevado Filabride Complex* [52].

The next sections consist of a general description of the main groups of rocks (metamorphic, sedimentary and Quaternary deposits). Their distribution in the study area is presented in the geologic map (Figure2.2).

### 2.4.1 Metamorphic rocks

The metamorphic rocks form the basement of the study area and correspond to the Nevado Filabride complex of Paleozoic, Permian and upper and middle Triassic ages and the Alpujarride complex of Permian and Triassic age [34].

- **Nevado Filabride Complex**: It is well exposed at the top and central portion of the Sierra Alhamilla, in the south and the Sierra de los Filabres in the roads to Velefique and Senes. The Nevado Filabride units comprises gneiss
2.4. Geology

Figure 2.2: Geologic map of the Tabernas study area. Source (34), and (2)

with tourmaline (P1γ), dark coloured mica schist and quartzites (PC–Pn), graphitic schists with garnet (PC-Pnε), micaschists gneiss and quartzites (P–TnA2) and marbles (Tn–A3). They have been pervasively metamorphosed from high-greenschist to amphibolite conditions [51].

- **Alpujarride Complex**: This complex occupies the intermediate to lower parts of the Sierra Alhamilla, and good outcrops of can be found in the road to the television tower and in some of the dry streams of this area. The rock types that belong to this complex are: Carbonate rocks (TaA), quartz-feldpathic schists (PC–Da), mica schists and phyllites (P–TaA). The rocks that belong to this complex show lower greenschist facies metamorphism [51],[75].

The contact between the Nevado Filabride and Alpujarride complexes is demarcated by mylonitic and cataclastic footwall rocks. This 0–400 m thick mylonitic zone has been termed the Betic Movement Zone (BMZ) [51] and [52], in [76]. Regional and local structural mapping from the mentioned authors suggest that a minimum displacement of the Alpujarride rocks over the Nevado Filabride rocks is the order of 50–80 km. This assumes nappe transport towards the N–NW, and deformation within the (BMZ) is complex and several components have been distinguished [76].

2.4.2 Sedimentary rocks

The sedimentary sequence range in age from Burdigalian to Quaternary and forms an intramontane basin in a faulted contact with the metamorphic units described above. It has been customary to subdivide the Neogene cover into Older Neogene (Burdigalian and Serravallian) and Younger Neogene (Tortonian-Pliocene), the last period is characterized by three major transgressive cycles: (i) Serravallian–Tortonian–
an, (ii) Messinian and (iii) Pliocene in decreasing order of importance [76]. They pass via fan-delta and playa-lake sediments with local continental intercalations into less deformed Tortonian-Messinian sequences of marine reefs and submarine fans deposited over broader areas [75].

The sedimentary rocks are represented by conglomerates and sandstones (Tbc11), conglomerates sandstones and marls (Tbc11–12), sandstones and marls (Tbcm12), limestone reefs (Tbcc12), gypsum (Tbcv12) and sandstones (Tb2).

2.4.3 Quaternary deposits

The Quaternary deposits are conformed by materials that are deposited in the forms of alluvial (Qal) and colluvial fans (Qc), terraces and river bed sediments. Generally they are composed by fragments of metamorphic and sedimentary rocks ranging from a few millimeters to 45 cm commonly immersed in a fine to coarse calcareous matrix.

The geology is an environmental component of high importance in the study of land degradation in the Tabernas area. The landscape morphology is highly controlled by the rock distribution, the related structures and later stages of evolution. The distribution of erosive and solution processes presents also a clear association with the different geologic units that exist in the area as will be described in Chapter 5.

2.5 Soils

The soils formation in the area of Tabernas is controlled by a variety of factors, where the composition of the geologic formations that act as parent materials is one of the most relevant. Climatic conditions of high aridity, morphologic and micromorphologic features (slope) and processes are also factors that influence the soil development. High rates of soil erosion also contribute to the sallow development of soil horizons [64].

Five taxonomic units with their correspondent soil associations have been described in [43] according to the guidelines presented in [21]. A short description of these taxonomic units is presented below.

- **Lithosols**: They are well distributed in the study area but the best locations are the high and steep lands forming part of different associations. They are soils with low evolution and the depth is limited by the bedrock at about 10 cm from the surface. Predominantly, they are developed from the weathering of siliceous and calcareous rocks [43].

- **Regosols**: They are formed from unconsolidated materials, but not from recent ones. They are developed from either siliceous and calcareous rocks forming Calcaric regosols and Eutric calcaric regosols, respectively; and with the Lithosolic Regosols are the most common associations in the area [43].

- **Lithosolic Regosols**: They are developed from siliceous materials, micaschists and quartzites from the Nevado Filabride Complex [43].

- **Calcaric Regosols**: Are one of the most abundant types of soils. The parent materials are generally calcareous rocks, conglomerates and rocks from the
Nevado Filabride Complex, such as mica schists and quartzites. They have abundant stones and the slope ranges from moderately tilted to steep terrain [43].

- **Eutric Regolos**: They are developed from schists and quartzites with moderate to highly steep slopes. They are well drained soils, present a stoniness of less than 50% and have an average depth of less than 20 cm [43].

## 2.6 Land Use

The most recent land use map of the Tabernas area corresponds to the year 1995. Thirteen different land use classes were identified using analog and digital aerial photographs and field observations [2]. The extension of each particular land use class is presented in Table 2.1. The information related to the changes in the land use pattern will be described in Section 2.8.2.

Table 2.1: Land use classes and their extension in the Tabernas area. Taken from [2].

<table>
<thead>
<tr>
<th>Landuse Type</th>
<th>1956/1981/1995</th>
<th>Period/Changes (%)</th>
<th>56 to 81</th>
<th>81 to 95</th>
<th>56 to 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry farm and tree plantation</td>
<td>1583.96/1621.04/1627.84</td>
<td>2.34/0.42/2.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry farming</td>
<td>7858.72/6415.6/5390.92</td>
<td>-18.36/-15.97/-31.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>799.28/1023.96/1039.88</td>
<td>28.11/1.55/30.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>0/25.92/25.92</td>
<td>25.92/0.00/0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigated tree, almond</td>
<td>196.8/541.2/787.16</td>
<td>175.00/45.45/299.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigated tree, olive</td>
<td>399.2/762.04/1338.92</td>
<td>90.89/75.70/235.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td>19.6/19.6</td>
<td>35.56/0.00/81.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed use</td>
<td>1086.24/1118.08</td>
<td>2.93/8.21/11.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None irrigated tree, others</td>
<td>34.96/52.44</td>
<td>60.16/60.00/50.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None-irrigated tree olive/almond</td>
<td>754.12/751.2</td>
<td>-0.39/0.00/0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protected/Hunting/Open space</td>
<td>14860.88/15230.48</td>
<td>2.49/0.42/2.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recreation</td>
<td>25.36/28.8</td>
<td>13.56/0.00/13.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban/settlement</td>
<td>47.76</td>
<td>60.22/0.00/60.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area (Ha)</td>
<td>27666.88</td>
<td>406.79/211.93/778.06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The dominant land use category is the one defined as protected-hunting-open spaces which occupies more than 55% and are constituted by private lands. Dry farming is the next category in extension with nearly 20%, while dry farming mixed with olives and almond plantations occupies almost 6%. Irrigation crops of olive and almond trees cover 8%. Small portions of the Sierras Alhamilla and Los Filabres present forest vegetation that covers nearly 4%. The category defined as mixed land use, which is represented by agricultural activities, such as cultivation of fruits, grape, olive, almond, dry farming, and other farm activities comprise nearly 4%. Land use categories like mining, industrial, recreation and residential activities represent a small portions of the study area and cover approximately 0.6% of it, adapted from [2].

## 2.7 Land Cover

The most recent land use map of the Tabernas area corresponds to the year 1995. Twelve land cover types where defined by the interpretation of analog and digital
Table 2.2: Land cover classes and their extension in the Tabernas area. Taken from [2].

<table>
<thead>
<tr>
<th>Landcover Type</th>
<th>1956 Year/Area (Ha)</th>
<th>1981 Year/Area (Ha)</th>
<th>1995 Year/Area (Ha)</th>
<th>56 to 81 Period/Changes (%)</th>
<th>81 to 95 Period/Changes (%)</th>
<th>56 to 95 Period/Changes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Bush and Grass Cover DBGC</td>
<td>4415.16</td>
<td>4318.48</td>
<td>4318.48</td>
<td>-2.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dense Bush cover with trees DBCT</td>
<td>399.32</td>
<td>490.72</td>
<td>490.72</td>
<td>22.89</td>
<td>0.00</td>
<td>22.89</td>
</tr>
<tr>
<td>Grass &amp; Bush DBCT</td>
<td>2803.28</td>
<td>2813.96</td>
<td>2813.96</td>
<td>0.38</td>
<td>0.00</td>
<td>0.38</td>
</tr>
<tr>
<td>Grassland GL</td>
<td>675.56</td>
<td>675.56</td>
<td>675.56</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mixed Forest MF</td>
<td>61.4</td>
<td>61.4</td>
<td>61.4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Non-natural Vegetation NNV</td>
<td>2690.76</td>
<td>3590.16</td>
<td>4573.4</td>
<td>33.43</td>
<td>27.39</td>
<td>60.81</td>
</tr>
<tr>
<td>Seasonal Cultivation SC</td>
<td>9212.36</td>
<td>7717.72</td>
<td>6649.84</td>
<td>-16.22</td>
<td>-13.84</td>
<td>-30.06</td>
</tr>
<tr>
<td>Sparse Bush and GrassCover SBGC</td>
<td>5367.76</td>
<td>5963.64</td>
<td>6003.64</td>
<td>11.10</td>
<td>0.67</td>
<td>11.77</td>
</tr>
<tr>
<td>Sparse bush cover with trees SBCT</td>
<td>1106.36</td>
<td>799.44</td>
<td>812.2</td>
<td>-27.74</td>
<td>1.60</td>
<td>-26.15</td>
</tr>
<tr>
<td>Without Vegetation WOV</td>
<td>197.04</td>
<td>332.08</td>
<td>348.04</td>
<td>68.53</td>
<td>4.81</td>
<td>73.34</td>
</tr>
<tr>
<td>Wood Forest - Plantation WFP</td>
<td>9.76</td>
<td>410.76</td>
<td>426.68</td>
<td>4108.61</td>
<td>3.88</td>
<td>4112.48</td>
</tr>
<tr>
<td>Wood Forest - Natural WFN</td>
<td>728.12</td>
<td>492.96</td>
<td>492.96</td>
<td>-32.30</td>
<td>0.00</td>
<td>-32.30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>27666.88</td>
<td>27666.88</td>
<td>27666.88</td>
<td>4166.49</td>
<td>24.50</td>
<td>4190.98</td>
</tr>
</tbody>
</table>

The dominant land cover types are bush and grass cover with and without trees. They cover more than 53% of the area and their type and density varies according to the nature and type of soil, hydrologic differences and human influences. Next to the bush and grass cover the diminishing seasonal cultivation covers about 24%. Non-natural vegetation, which constitutes all tree-type of covers that were introduced by human beings as cultivation, excluding the tree forest plantations, is the fourth-largest cover type that was identified in the referenced study with an extension of 16.5% of the area. The tree forest plantations of pines and eucalyptus have an extension of 1.54%. The dark green natural covers on Sierra Alhamilla, though it is widely dispersed, covers nearly 2%, adapted from [2].

2.8 Human Activities

Human activities have exerted great influence in the natural conditions of the desert of Tabernas through time. Socio-economic pressures have changed the natural dynamics of the area and environmental changes of great extent have been detected in the land use and land cover patterns at least in the last 50 years. The human activities that will be consider for the analysis of the two indicators of land degradation will be the changes in the land use and land cover through three different periods of time (1956, 1981 and 1995) and the road construction and development during the same years. In this section, a characterization of these aspects will be presented as well as a brief comment on the mining activities that have taken place in the study area. The influences and relationships with the selected indicators will be discussed in Chapters 5 and 6.

2.8.1 Mining activities

The variety of geologic formations makes the study area suitable to host metallic as well as industrial minerals. The mining activities in the study area started in the
1890s where carbonated rocks from the Alpujarride Complex were exploited due to their high content and quality of iron minerals, in the surroundings of the towns Lucainena de las Torres and Turrillas in the Sierra Alhamilla [23].

The mining concessions at these sites of the Sierra Alhamilla were aligned from east to west and topographic and structural controls conditioned the pattern of the mineralization. The first works where carried out by an open pit exploitation system and in 1901 the first gallery was excavated and an iron seam was discovered. The approximate dimensions were 37x10x2500 m with a calculated weight of 1850000 ton. Later on, six more galleries were excavated with a total length of 1500 m, which permitted to increase the mineral reserves [23].

The mining works in Lucainena de las Torres were held until 1942, when multiple problems in the exploitations, lack of external market for the minerals in Europe and the Civil War in Spain were the main causes for the “Compañía Minera Sierra Alhamilla” which was the owner of the mines and infrastructure decided to liquidate the business.

Nowadays the mining activities are represented by the exploitation of sands and gravels deposited as alluvio-colluvial materials (Qc). The active mine site is located at the north of Tabernas and south of the Almería solar plant. The coordinates of the center of the exploitation are (X:555759,Y:4103942) and covers an area of approximately 270 by 200 m. The access from Tabernas is approximated 2.7 km north, from the cross of the national road CN-340 with the road to Velefique where there is an access to the mining site.

The materials are exploited by the open pit system. The banks of exploitation are approximately between 10 and 15 m high and heavy machinery like bulldozers, chargers and tip carts are used to pull out and transport the material to a classifier and after it is ready to go to the consuming centers.

Next to the active site, at approximately 400 m towards the north-west there is an abandoned mine that nowadays it is used as a waste disposal site of the Tabernas municipality. The center of the exploitation is at (X:556063,Y:4104342) and covers an area of approximately 300 by 200 m. According to the morphology existent, the mining method and operations were similar to the one that is active at the moment of the visit.

An abandoned mining site corresponding to a gypsum quarry is located 500 m South from the junction of the CN-340 and the road Tabernas–Uleila del Campo. The center of the exploitation is at (X:562837,Y:4104281) and the total area affected by the mining activities corresponds to 390 by 250 m, distributed in various fronts. The exploitation system corresponded to an open pit with one single bank, leaving vertical slopes with a height of approximately 15 to 20 m. Due to the hardness of the gypsum rock it was necessary to use explosives to pull out the material. As part of the activities developed at the site there was a plant for the reduction of particle size which seems to be the only beneficiating process. At the moment of the visit, all the installations were abandoned and there was no restoration practices.

### 2.8.2 Land use changes

The land use in the Desert of Tabernas has been interpreted as the most dynamic environmental element that has undergone a change in the study area and reflects
2.8. Human Activities

past environmental, as well as socio-economic conditions. The land use changes were mapped using analog and digital aerial photographs from 1956, 1981, 1995 and field data collection [2]. The results are presented in Table 2.1 and Figure 2.3.

The reduction of the dry farming practices is the biggest change that was identified. During the past 45 years, the total dry farm shrunk from 7957 hectares to 5351 hectares showing a reduction of 32%. The non-irrigated trees (NITO), mining and quarrying (MQ) and the irrigated trees almonds and olives, (IRTA) and (IRTO), classes have shown a big increase from 1956 to 1995 with 386, 345%, 300% and 235% respectively, adapted from [2].

2.8.3 Land cover changes

The land cover changes in the study area were mapped as the land use changes using analog and digital aerial photographs from 1956, 1981, 1995 and field data collection by [2]. The results are presented in Table 2.2 and Figure 2.4.
2.8. Human Activities

The largest change was the decrease in seasonal cultivation (SC) cover. This class has lost a total of 2562 Ha of land. Followed by the sparse bush cover with trees (SPCT) class that lost a total of 306 hectares. Similarly, the natural tree cover on the Sierra Alhamilla has lost a total area of 235 Ha and the dense bush and grass cover (DBGC) about 97 Ha.

On the contrary, there was a dramatic increase in the tree plantation cover (WFP), which presents an increase from 10 Ha in 1956 up to 426 Ha in 1995. The second largest increment is for the non-natural vegetation (NNV) class. From 2690 Ha in 1956 to 4573 Ha in 1995.

2.8.4 Asphaltisation

Asphaltisation is considered as a process that lead to the total and irreversible soil loss in an area because of it remains permanently buried by the combined effects of actions and activities of civil engineering, which include the preparation and topographic conditioning of the area to be urbanized, land movements, digging, fences, talus, etc. [59].

Table 2.3 and Figure 2.5 present the evolution of the road construction in the study area. From a total of 51.55 Km of roads, in 1950; an increase up to 83.46 Km in 1985 to a final length of 115.91 km in the year 2000 was observed [2]. The classes that show a high increase in length of constructed roads are the asphalted roads (7–9 m width), and asphalted roads roads (5–6 m width). Road classes like gravel and asphalted roads (3–4 m width) show a decrease from 1950 to 2000, which was interpreted as their conversion to one of the previous described classes.

Table 2.3: Road construction in the Tabernas area from the 50s to the year 2000 (adapted from [2]).

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Year/Length in km.</th>
<th>1956</th>
<th>1981</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asp. Rd. 7-9m</td>
<td></td>
<td>38.08</td>
<td>21.65</td>
<td>55.60</td>
</tr>
<tr>
<td>Asp. Rd. 5-6m</td>
<td></td>
<td>0.00</td>
<td>14.09</td>
<td>27.40</td>
</tr>
<tr>
<td>Asp. Rd. 3-4m</td>
<td></td>
<td>0.00</td>
<td>17.52</td>
<td>12.01</td>
</tr>
<tr>
<td>Gravel road</td>
<td></td>
<td>23.47</td>
<td>30.21</td>
<td>20.90</td>
</tr>
<tr>
<td>Total/Overall increase</td>
<td></td>
<td>61.55</td>
<td>83.46</td>
<td>115.91</td>
</tr>
<tr>
<td>Area in Ha</td>
<td></td>
<td>112.52</td>
<td>152.2</td>
<td>194.47</td>
</tr>
</tbody>
</table>

Asp. Rd. 7-9: Asphalted Road 7 to 9 m width
Asp. Rd. 5-6: Asphalted Road 5 to 6 m width
Asp. Rd. 3-4: Asphalted Road 3 to 4 m width
2.8. Human Activities

Figure 2.5: Road construction in the Tabernas area from the 50s to the year 2000.
Chapter 3
Remote Sensing to Assess Land Degradation in Tabernas

3.1 Introduction
The use of remote sensing techniques to study the land degradation processes in the Mediterranean type of environments has been extensively applied during the past decade. New developments have emerged from different projects (MEDALUS, DEMON, ELANEM) and new sensors are being tested to assess their capabilities to improve the results already obtained. This chapter is devoted to describe the more relevant characteristics of the remotely sensed data used to support the mapping of geomorphologic units and morphodynamic processes to assess the indicators of land degradation in the study area of Tabernas. The techniques applied to process raw data, such as radiometric, geometric corrections and image enhancements to obtain interpretable products will be discussed. Visual or digital image interpretation?...is the question that will be addressed at the end of the chapter to analyze the capabilities of remotely sensed data to assess the aspects related to land degradation.

3.2 Remotely Sensed Data Characteristics
Image interpretation has proven to be of great value for geomorphologic as well as other related types of earth sciences mapping. The interpretation of remotely sensed images, such as aerial photographs and satellite images, permits to effectively plan and optimize the execution of the fieldwork stages. It also has become critical to validate the information obtained from the interpretation stage by the fieldwork itself, when ground truth data is gathered.

In the process of image understanding and interpretation of raw data, a series of steps are developed by the interpreter. It starts with the discrimination process, where the interpreter looks for criteria that permit to separate the target objects from ones that have little relevance to his/her particular work. For geomorphologic mapping, this stage permits to distinguish broad physiographic complexes. The discrimination step is followed by the stages of detection and categorization, where more selective information is obtained e.g. geomorphologic units. Finally the interpreter
identifies and classifies the recognized objects and features e.g. drainage pattern, landforms, human-made features. This final stage integrates all the previous steps in order to produce a photo or image geomorphologic map.

The criteria used to perform the visual interpretation correspond to classical image characteristics and terrain expressions like tone, color, shape, texture, pattern, morphology, drainage and land cover. For this task, three types of image data were used in this study: analog and digital aerial photographs, LANDSAT TM and ASTER imagery. Their characteristics will be described in the following paragraphs, where more attention will be given to ASTER because it is a relatively new sensor, which is being used extensively for a wide variety of applications in the earth sciences.

3.2.1 Aerial photographs

Black and white aerial photographs in analog and digital format were available for this study. They were taken by the “Junta de Andalucía”, the environmental corporation with jurisdiction in the study area. In total, 174 photographs of different flights for the years 1956, 1981 and 1995, composed the dataset.

- The set of the year 1956 consists of 50 photographs taken in 5 strips of east-west flight lines at approximately 1:20,000 scale. It was acquired in three different periods. Four stripes were acquired between the 12th and the 13th of August. The last strip was acquired in February 19th 1957.

- The set of 1981 comprises 44 photographs taken in 4 strips of east-west flight lines at approximately 1:33,000 scale.

- The set of 1995 consists of 6 strips of 80 photographs taken in east-west flight lines at approximately 1:20,000 scale. The time of capture was around noon with almost vertical camera projection center and 151.92 mm of focal distance.

The fact that the time of acquisition for the set of 1956 was different brings some difficulties in the interpretation process. The tonal variations found specially for the set acquired in February reduce its interpretability. The sets of 1981 and 1995, regardless of the small scale differences present a better quality in terms of tonal variations among them.

Ortho-photo mosaics were generated from the aerial photographs to detect the changes in the land use/cover patterns in the Tabernas area [2]. The advantage of ortho-photos is that they do not contain the scale, tilt, and relief distortions that characterize normal aerial photographs. In essence, ortho-photos are ‘photo-maps”. Like maps they, have one scale, and like photographs, they show the terrain in actual detail [40]. This becomes important when interpreting them because the boundaries can be traced precisely with no displacement distortions. The generation of the ortho-photo mosaics involved the scanning of analog aerial photograps, ortho-rectification using the DEM and a 1:10,000 topographic map, color separation and image resampling using a pixel size of 5 m [2]
3.2.2 Landsat imagery

The LANDSAT satellite system was designed to collect 15 m resolution “panchromatic” data and six bands in the visible, near infrared (NIR), and mid-infrared (MIR) spectral regions at a spatial resolution of 30 m. A seventh band in the thermal infrared (TIR) range was incorporated with a spatial resolution of 60 m. The satellite flies in a sun-synchronous orbit at 705 m of altitude. The scanning mechanism is whiskbroom with 16 days of revisiting time period. The size of a nominal Landsat scene is 185 km [40].

To study the land degradation process in the Tabernas study area, a Landsat 5 image from the year 1986, was used. The scene boundaries have the coordinates: 38°04'29" N, 36°52'06" N, 0°52'25" W and 0°22'09" W. The path/track is 199 and the row/frame is 34. The images were provided by the Image Processing Laboratory (IPL) from ITC in “img” format.

3.2.3 ASTER imagery

ASTER stands for Advanced Spaceborn Thermal Emission and Reflection Radiometer. It is the only high-spatial resolution multispectral imager on Terra, a satellite launched in December 1999 as part of the NASA’s Earth Observing System (EOS), whose goal is to obtain a better understanding of the interactions between the biosphere, hydrosphere, lithosphere and atmosphere (modified from, http://asterweb.jpl.nasa.gov/default.htm).

ASTER is a sensor composed of three individual subsystems, visible and near infrared Radiometer (VNIR), short-wave infrared Radiometer (SWIR) and thermal infrared Radiometer (TIR). This design was done in order to provide a more advanced sensor than the ones previously operating and to meet the scientific requirements, especially concerning to the SWIR and TIR bands.

The instrument has a wide spectral range and consists of 15 bands. Three bands in the VNIR, with a spectral range (0.5-1 μm) and 15 m spatial resolution. The possibility to obtain stereo images is available due to the fact that the third band is acquired by a nadir and a backward looking telescopes. In the SWIR, it has six bands, with a spectral range (1.0-2.5 μm) and a spatial resolution of 30 m. In the TIR, ASTER has five bands with a spectral range (8-12 μm) and 90 m spatial resolution.

The satellite flies in a sun-synchronous and near polar orbit at 705 km. It will cross the equator in the morning at approximately 10:30 AM. The cross-track pointing capability in all telescopes ((24 degrees for VNIR, 8.55 for SWIR and TIR)) is sufficient to allowing imaging of any point on Earth over the 16 day revisit period of the EOS-A Platform orbit. A different type of telescope is employed for each optical sensing subsystem. The scanning mechanism for the VNIR and SWIR is pushbroom and uses CCD (Charged Coupled Detectors). The TIR uses whiskbroom scanning with 10 HgCdTe detectors per spectral band (50 detectors in total). The swath is 60 Km (across-track), by 60 Km (along-track), which is the size of a nominal scene.

There are three types of ASTER data products that ASTER GDS (Ground Data System) produces and provides. The standard, the semi-standard, and the special products:

- **Standard Products**: Products of this type are distributed based on the DPR
3.2. Remotely Sensed Data Characteristics

(Data Product Request) submitted by the users. They are unprocessed (Level 1A) and processed (Radiance at sensor, Level 1B) with standard parameters, including radiometric and geometric correction. Relative emissivity (Decorrelation stretch, 2A02), relative reflectivity (Decorrelation stretch, 2A03)

- **Semi-Standard Products**: Products of this type will only be produced in Japan, normally, depending on the production policy of each working group. Among those are, orthographic images and relative digital elevation models (DEM). Data Production Requests for products of this type are not guaranteed.

- **Special Products**: In principle, this type of products are not available to any users. However, you can consult with the member of the Science Team responsible for the special products that you wish to obtain. Orthographic images with precise geometric correction and several thematic maps belong to this type of products.

As a high spatial and spectral resolution, ASTER can meet a variety of applications in the earth and related sciences. One of the greatest advantages of the ASTER data is that can be obtained “free of charge” by running a query for the area of interest through the internet at the ASTER home page (http://asterweb.jpl.nasa.gov/default.htm), (See Appendix 1). The procedure can be easily followed, is not time consuming and different order formats (FTP, CD-ROOM, DVD, 5 mm) are available. The disadvantages are the file formats in which the products are received. In the case of 1A, 1B, 2A02-03 images, an “hdf” (Hierarchical Data Format) is the format delivered to the user. Then, the necessity of specialized software, like ENVI, Geomatica GeoGateway, DF Explorer, IDL, etc., to visualize and export to other formats is required.

For this study, a query was run in the internet to obtain ASTER data and test their capabilities to map geomorphological features and processes. Six datasets of images corresponding to four 1A and one 1B products, each of them composed of 15 bands in VNIR, SWIR and TIR were obtained. In order to make a selection of the best dataset that could be useful for the purposes of the study, a visualization of each of the images using ENVI software was carried out. The type of product and cloud cover percentage were the main criteria that led to a final decision on which of the datasets acquired will be used.

ASTER 1B products are radiometrically and geometrically corrected and they would be the most suitable product to work with. The problem encountered with the 1B dataset was high percentage of clouds in the images and they were discarded. ASTER 1A products are radiometrically and geometrically uncorrected. The criteria used to select a dataset that meets the requirements of this project was again the cloud percentage of the scenes. Among the obtained products, there was one without cloud coverage and finally it was selected to carry out the processing and interpretation. The date of acquisition was July 14th of the year 2000.

In Table 3.1, a summary of the characteristics of each of the remotely sensed data used, as well as the main features that can be extracted when performing a visual interpretation is presented. In a sense, this table shows partially the potentials and limitations of the remotely sensed data for geomorphologic mapping and the identification of areas affected by morphodynamic processes. This aspect will be presented...
3.3. Image Processing

This section describes the procedures and methods followed in order to transform raw image data to obtain enhanced products that can be useful in the geomorphologic mapping. Basically it deals with six topics: radiometric and geometric corrections, image geo-referencing and image enhancement, color composites generation.

Table 3.1: Remotely sensed data characteristics.

<table>
<thead>
<tr>
<th>AERIAL PHOTOGRAPHS AND ORTHO-PHOTO MOSAICS</th>
<th>ASTER</th>
<th>LANDSAT 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral Range</strong></td>
<td><strong>Spatial Resolution (m)</strong></td>
<td><strong>Spectral Range (um)</strong></td>
</tr>
<tr>
<td>Visible range in gray scale</td>
<td>5m</td>
<td></td>
</tr>
<tr>
<td>VNIR</td>
<td>1</td>
<td>0.52-0.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.63-0.69</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.76-0.86</td>
</tr>
<tr>
<td>SWIR</td>
<td>4</td>
<td>1.60-1.70</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.145-2.185</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.185-2.225</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.235-2.285</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.305-2.360</td>
</tr>
<tr>
<td>TIR</td>
<td>9</td>
<td>8.125-8.475</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.475-8.825</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>8.75-9.275</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>10.25-10.95</td>
</tr>
<tr>
<td>COSTS</td>
<td>Free (at the moment)</td>
<td>US $ 600 per scene (approx.)</td>
</tr>
</tbody>
</table>

POTENTIALS TO RECOGNIZE ELEMENTS FOR GEOMORPHOLOGIC MAPPING

- Aerial photographs allow stereoscopic interpretation.
- The analysis is limited to visual characterization of geomorphologic features.
- Geomorphologic units.
- Individual landforms or terrain elements (scarps, slopes).
- Extensive areas affected by morphodynamic processes.
- Individual Morphodynamic processes.
- Complete and detailed characterization of drainage network.
- Visual identification of land cover types associated with morphodynamic processes.
- The fact that a nadir and a backward looking telescopes acquired images in Band 3, allows the possibility of stereoscopic vision and high resolution DEM generation (*).
- Broad physiographic provinces.
- Geomorphologic units (with scale and resolution limitations).
- Extensive areas affected by morphodynamic processes.
- Visual and spectral characterization of land cover types (bare soils, vegetated areas, sparse vegetation).
- Major drainage network elements.

LIMITATIONS TO RECOGNIZE ELEMENTS FOR GEOMORPHOLOGIC MAPPING

- Ortho-photo mosaics do not allow stereoscopic interpretation.
- Broad physiographic provinces.
- The spectral characterization is restricted to relative evaluation (low, intermediate and high reflectance).
- Individual landforms or terrain elements (scarps, slopes).
- Detailed characterization of drainage network.
- Individual Morphodynamic processes.
- Do not allow stereoscopic interpretation (if there is no availability of DEM).
- Individual landforms or terrain elements (scarps, slopes).
- Detailed characterization of drainage network.
- Individual Morphodynamic processes.

3.3 Image Processing
3.3. Image Processing

Raw image data were acquired in different file formats. The Landsat images were provided in “img” format. The original ASTER images were received from the EOS-GDS in “hdf” format and were exported to “lan” format using the software ENVI 3.4. Subsets of a smaller area covered from the original scenes and a bigger area than the one covered by the aerial photographs were generated from the original Landsat and ASTER images using the software ERDAS IMAGINE 8.4.

3.3.1 Radiometric correction

Six bands corresponding to the VNIR and Mid-IR Landsat images of 1986 were used in this study. The thermal band was not included in the analysis due to its poor quality due to a high stripping effect. There were difficulties to read the meta-files that contain the information to carry out the radiometric correction and it was not possible to perform this step. Atmospheric corrections using the minimum digital number (DN) value were performed for the six selected bands. This method offsets the (DN) histograms of each band so that pixels in dark shadow cast by steep terrain slopes have corrected DN values of zero [63].

A computer program, named ASTERCOR, written in Interactive Data Language (IDL) and developed and provided by the IPL of ITC was used to perform the radiometric correction of the ASTER level 1A data. The program uses the table for sensor calibration provided within the “hdf” file that contains the image data and was run using the IDL module of ENVI software, version 3.4. The program worked properly for the VNIR bands. An improvement in the quality of the images consisted in a high reduction of the stripping effect was observed after running the ASTERCOR program. For the SWIR and TIR bands the appearance of the stripping effects did not improved after running the program. This fact creates a constraint for this project, which consists in the limitation of the analysis of the ASTER dataset only for the VNIR spectral range.

3.3.2 Geometric corrections and image geo-referencing

Raw image data is affected by geometric distortions that do not permit its integration with other data and generate new thematic information. The distortions in satellite images can be due to a variety of factors like, sensor geometry, scanner and platform instabilities, earth rotation and curvature, [31]. The different distortions of the images can be corrected by means of geo-referencing them to existing maps or even geo-referenced images.

Both Landsat and ASTER VNIR images were geometrically corrected by geo-referencing them finding common ground control points in the ortho photo mosaic of the year 1995. The process of sampling the ground control points was easier for the VNIR ASTER images due to its higher spatial resolution (15 m), twice as Landsat imagery in this spectral range (Table 3.1).

For ASTER data, total of eight points were sampled and a first order or affine transformation was computed. A Root Mean Square Error (RMSE) or sigma of 0.170 pixels, which is equal to 2.57 m. In the Landsat images, a total of nine control points
3.4. Image Enhancement

<table>
<thead>
<tr>
<th>Band</th>
<th>Lan86B1</th>
<th>Lan86B2</th>
<th>Lan86B3</th>
<th>Lan86B4</th>
<th>Lan86B5</th>
<th>Lan86B7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lan86B1</td>
<td>1</td>
<td>0.99</td>
<td>0.97</td>
<td>0.91</td>
<td>0.86</td>
<td>0.89</td>
</tr>
<tr>
<td>Lan86B2</td>
<td>0.99</td>
<td>1</td>
<td>0.99</td>
<td>0.95</td>
<td>0.9</td>
<td>0.93</td>
</tr>
<tr>
<td>Lan86B3</td>
<td>0.97</td>
<td>0.99</td>
<td>1</td>
<td>0.97</td>
<td>0.93</td>
<td>0.95</td>
</tr>
<tr>
<td>Lan86B4</td>
<td>0.91</td>
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<td>0.97</td>
<td>1</td>
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</tr>
<tr>
<td>Lan86B5</td>
<td>0.86</td>
<td>0.9</td>
<td>0.93</td>
<td>0.95</td>
<td>1</td>
<td>0.99</td>
</tr>
<tr>
<td>Lan86B7</td>
<td>0.89</td>
<td>0.93</td>
<td>0.95</td>
<td>0.96</td>
<td>0.99</td>
<td>1</td>
</tr>
</tbody>
</table>

Mean: 27.38, 19.29, 26.05, 20.42, 40.62, 24.75
Std. Dev: 19.63, 0.14, 19.57, 16.3, 32.91, 19.5

were sampled. The same type of transformation was selected and a sigma of 0.447 pixels, which is equal to 13.32 m, was obtained.

After geo-referencing an image, it will have coordinates for each pixel, but it still have geometric distortions and can not be adapted to a master map or image. The process of geo-coding or re-sampling helps to solve this problem and creates a new image in which the pixels are arranged in the geometry of a master image. The resolution of the new image is equal to the resolution of the master image or map [31]. ASTER images were re-sampled to 15 m pixel size. For the Landsat images a pixel size of 30 m was used for the re-sampling operation.

3.4 Image Enhancement

Image enhancement consists of a series of process applied to the satellite images in order to improve their visual interpretability [40]. Among those processes linear stretching and histogram equalization were applied in both Landsat and ASTER data. The results obtained for visual interpretation, show that the linear stretching method was more effective than histogram equalization. The aspect of the images when the last method was applied present higher density of areas with high reflectance, with a large amount of lighter patches; reducing ostensively their interpretability.

3.4.1 Sum normalization

The technique called “sum normalization approach” [57], [77] in [63] was applied to the Landsat image. It consists in the division of individual bands by the sum of the six bands. The effects of this process is that color information is retained in a reflectance spectrum, but discounts albedo [57] in [63]. The six bands corresponding to the VNIR and Mid-IR of the Landsat image were sum normalized.

After the sum normalization of individual bands, image statistics, like correlation matrix; were calculated for non normalized and sum normalized images. From Table 3.2 it can be noticed that non normalized individual Landsat images are highly correlated with each other (coefficients close to 1), which means a redundancy in the spectral information contained in the six bands used.
3.4. Image Enhancement

Table 3.3: Correlation matrix of sum normalized Landsat image, bands 1 to 7 (B1...B7).

<table>
<thead>
<tr>
<th></th>
<th>SNorB1str</th>
<th>SNorB2str</th>
<th>SNorB3str</th>
<th>SNorB4str</th>
<th>SNorB5str</th>
<th>SNorB7str</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNorB1str</td>
<td>1</td>
<td>0.93</td>
<td>0.85</td>
<td>0.43</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>SNorB2str</td>
<td>0.93</td>
<td>1</td>
<td>0.91</td>
<td>0.55</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>SNorB3str</td>
<td>0.85</td>
<td>0.91</td>
<td>1</td>
<td>0.64</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>SNorB4str</td>
<td>0.43</td>
<td>0.55</td>
<td>0.64</td>
<td>1</td>
<td>0.69</td>
<td>0.62</td>
</tr>
<tr>
<td>SNorB5str</td>
<td>0.22</td>
<td>0.28</td>
<td>0.42</td>
<td>0.69</td>
<td>1</td>
<td>0.94</td>
</tr>
<tr>
<td>SNorB7str</td>
<td>0.25</td>
<td>0.32</td>
<td>0.46</td>
<td>0.62</td>
<td>0.94</td>
<td>1</td>
</tr>
</tbody>
</table>

Mean 83 93.39 114 75.53 107.66 101.24
Std. Dev 68.11 71.50 81.12 54.91 80.04 76.20

Table 3.4: Principal components of sum normalized Landsat image, bands 1 to 7 (B1...B7).

<table>
<thead>
<tr>
<th></th>
<th>SNorB1</th>
<th>SNorB2</th>
<th>SNorB3</th>
<th>SNorB4</th>
<th>SNorB5</th>
<th>SNorB7</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1SNorLan86</td>
<td>0.371</td>
<td>0.421</td>
<td>0.514</td>
<td>0.303</td>
<td>0.412</td>
<td>0.399</td>
</tr>
<tr>
<td>PC2SNorLan86</td>
<td>0.404</td>
<td>0.391</td>
<td>0.304</td>
<td>-0.119</td>
<td>-0.566</td>
<td>-0.507</td>
</tr>
<tr>
<td>PC3SNorLan86</td>
<td>0.323</td>
<td>0.048</td>
<td>-0.101</td>
<td>-0.857</td>
<td>0.047</td>
<td>0.382</td>
</tr>
<tr>
<td>PC4SNorLan86</td>
<td>0.564</td>
<td>0.148</td>
<td>-0.713</td>
<td>0.234</td>
<td>0.244</td>
<td>-0.191</td>
</tr>
<tr>
<td>PC5SNorLan86</td>
<td>-0.184</td>
<td>0.427</td>
<td>-0.329</td>
<td>0.213</td>
<td>-0.561</td>
<td>0.562</td>
</tr>
<tr>
<td>PC6SNorLan86</td>
<td>0.492</td>
<td>-0.681</td>
<td>0.124</td>
<td>0.243</td>
<td>-0.366</td>
<td>0.293</td>
</tr>
</tbody>
</table>

Variance % 64.46 27.6 4.14 2.15 0.98 0.67

The results presented in Table 3.3 suggest that sum normalized bands 1, 2 and 3 present a high correlation. The same occurs for bands 5 and 7; and the less correlated bands are bands 1, 5 and 4.

The information obtained from the image statistics was used to generate a color composite for visual interpretation and spectral characterization of eroded features and other land cover types. The best combination according to the statistics suggests that the less correlated sum normalized bands (1,4 and 5) offer the best results for this task. The characteristics of the color composites will be presented in Section 3.4.3.

3.4.2 Principal component analysis

Extensive inter-band correlation is a problem frequently encountered in the analysis of multispectral image data. Principal component transformation is a technique designed to reduce such redundancy in multispectral data. This transformation may be applied either as an enhancement operation prior to visual interpretation of the data or as preprocessing prior to automated classification of the data [40].

Principal component analysis transforms a multi-band image into a set of orthogonal images that carry new information. After the calculations, the new images are ordered in terms of their amount of variance. The first two or three principal components will carry most of the real information of the original data set, while the successive components describe only minor variations (sometimes only noise) [31]. The principal components for the six sum-normalized Landsat bands were calculated using ILWIS 3.0. The statistics are presented in Table 3.4.
The results obtained indicate that the first three principal components account for about 96.2% of the spectral variation presented in all six bands. Visual examination of principal components 4, 5 and 6 are largely composed by noise. A high speckle effect is observed and hardly any type of information that helps to recognize land cover features and identify eroded areas can be retrieved from them. Then, the first three principal components were used to generate a color composite for visual interpretation and further classification.

3.4.3 Color composites

Three color composites were generated from the combinations of sum normalized and principal components enhanced Landsat, and ASTER VNIR bands. The purpose was to identify, extrapolate and correlate the image interpretation with the information acquired in the field and extract characteristics for different land cover types, with special attention in the areas affected by erosive processes and the associated land covers. During the image interpretation and fieldwork stages, it was observed that the areas covered by bare soil, resulting from the loss of vegetative cover or land preparation for agricultural practices, and those covered by sparse vegetation present a clear association with erosive processes.

A combination of sum normalized Landsat bands 451 in red green and blue, respectively, highlights the overall spectral variability of individual bands according to the results obtained from the correlation matrix presented in Table 3.2. This color composite is presented in Figure 3.1.

The areas corresponding to forest and river-side vegetation, located in the Sierras Alhamilla and Los Filabres can be clearly identified, as they present reddish, pinkish and orange colors. The areas with dense grass and bush covers are associated with light greenish colors. The blueish and purple colors present a strong association with areas identified as bare soil and covered by sparse herbaceous vegetation. They are located predominantly in the badlands and the foothills of the Sierra de Los Filabres.

Another color composite was generated using the first three principal components of the sum-normalized Landsat image, Figure 3.2. Principal component one was assigned to the red, the second principal component was assigned to green and the third to the blue color. The selection of this combination corresponds to those principal components that carry most of the information of the sum normalized bands. This is evident from the statistics presented in Table 3.4.

The visual inspection of this image shows that the areas covered by bare soil and affected by erosive processes present a characteristic light yellow and orange colors. This combination was useful to identify an area affected by gypsum quarry, located in the east-central part of the image. It presents a strong yellow color. The most dominant land cover in this place is high reflective gypsum rock and soils. The areas where sparse vegetation is the dominant land cover are characterized by light purple colors. The forest and river-side vegetation present in this image dark tones of greenish colors.

The VNIR bands of the ASTER image were used to create a false color composite, Figure 3.3. The near infrared, band 3, was assigned to the red, band 2 to green and band 1 to blue. The selection of bands obeyed to the facility to identify green vegetation due to the peak that it presents in the near infrared region of the electromagnetic spectrum.
3.4. Image Enhancement

In the image, the forest plantations and river-side vegetation present red colors. The bare soil surfaces resulting from the weathering of the sedimentary rocks, where the terrain is prepared for agriculture present a high reflectance in the individual bands and a characteristic white color in the color composite. It permits to differentiate them from areas where the bare soil is the result of erosive processes, which are characterized by blueish and light brownish colors. The dense herbaceous and bushy vegetation presents dark blueish and greenish colors.

The characteristics identified during the visual inspection of the Landsat and ASTER images, as well as the information collected during the fieldwork stage and the interpretation of ortho-photomosaics were used during the next step of this work, which will be presented in the next section.
3.5 Image classification

Image classification is a process to extract thematic information from satellite images. It can be performed on one single band (image slicing) or on multiple bands (multi-spectral image classification). Unsupervised and supervised classifications are two different methods to classify images. The first one is based on classification algorithms, which are completely automated by the computer. In supervised classification, the person behind the computer defines the thematic classes according to particular interests (land use, land cover, geology, etc.). He/she “trains” the classifier by sampling pixels with similar spectral characteristics and assigns them to particular classes.

The individual bands of a satellite image are termed “features”. In three bands, the value of a pixel represents a three-dimensional vector, the “feature vector”, that can be plotted in a three-dimensional space or “feature space”. All the pixels that belong to a certain class will form a cluster in the feature space [31].

The selection of a classification algorithm is the next step to carry out. The more common algorithms for image classification are [5]:

Figure 3.2: Color composite of sum normalized Landsat image, Bands 451 in RGB, respectively.
3.5. Image classification

Figure 3.3: False color composite of ASTER Bands 321 in RGB, respectively

- **Box classifier**: It is the most simple classification algorithm. It is based on upper and lower values for each of the classes, which defines a box-like area in the feature space. The disadvantage of the method is the overlap between classes and in this case, a pixel is arbitrarily labelled in the first box it encounters.

- **Minimum distance to mean classifier**: It is based on the cluster centers on the calculation of Euclidean distances from an unknown pixel to various cluster centers. The unknown pixel is assigned to that class to which the distance is least. An advantage of this method is that it does not take into account class variability.

- **Maximum likelihood classifier**: It considers not only cluster centers but also their shape, size and orientation. It is based on the calculation of the statistical distance, which is the probability that a specific observation belongs to a specific cluster (class) and then, the pixel is assigned to the cluster with the highest probability.
3.5.1 Classification of sum-normalized Landsat images

Six land cover classes were defined to obtained a supervised classification of the color composites generated from the combination of sum-normalized Landsat bands 4, 5, 1 and principal components 1,2 and 3 in red green and blue, respectively. The land cover classes are:

- Forest and River-side Vegetation (F)
- Dense Bush and Grass (DBG)
- Sparse Bush and Grass (SBG)
- Eroded Land (E)
- Bare Soil prepared for Agriculture (BSA)
- Agricultural Land (A)

The classification algorithm selected was the maximum likelihood classifier. Its statistical basis to assign a pixel to a particular class offers more advantages than the box classifier, specially where there is certain spectral overlap among individual classes, as in this case. Also, this classifier offers more advantages than the minimum distance classifier, in terms that cluster shapes, sizes and orientations are taking into consideration. The resultant maps after running the classifier were filtered using the majority type of filter. The majority filter consists of a matrix of 3*3 pixels and assigns the predominant land cover class for a pixel and its eight neighbours [31]. This filter smooths the original map and a better appearance is obtained.

The classified sum normalized bands 4, 5 and 1 is presented in Figure 3.4. The statistics of the training samples obtained for the land cover classes are presented in Figure 3.5. The classes “Forest and River-side Vegetation”, and “Dense Bush and Grass Cover” present a different spectral response in the individual bands and a good separability among them can be established. For the classes “Dense Bush and Grass Cover” and “Sparse Vegetation” band 4 offers good possibility to separate them due to their different spectral values. The land cover classes “Agricultural Land”, “Bare Soil for Agriculture” and “Eroded Land”, present a similar spectral response in bands 1 and 4. In the sum normalized band 5, the same classes, except the “Agricultural Land” present more contrasting values that permit their differentiation. The classes “Eroded Land” and “Sparse Vegetation” have different spectral response in the three bands considered for the analysis. This permits to distinguish them from the other land cover types.

The feature spaces of the band combinations of sum normalized bands 4, 5 and 1 is presented in Figure 3.6. It can be observed that the clusters for the classes “Forest and River-side Vegetation”, dense bush and grass, and eroded land do not present a high overlap among themselves. This fact confirms the class separability introduced in the previous paragraph. The rest of the classes present high overlap and hardly any differentiation can be observed, which introduces a limitation to spectrally characterized those land covers types.

The color composite obtained from the combination of principal components 1,2 and 3 was also used to perform a supervised classification. The training process was
3.5. Image classification

Figure 3.4: Classified Landsat bands 4, 5, 1 in RGB, respectively.

Figure 3.5: Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite obtained from the combination of bands 4, 5, 1 in RGB, respectively, of sum normalized Landsat image.
3.5. Image classification

Figure 3.6: Feature spaces of classified Landsat sum-normalized bands 4,5,1.

carryied out using the data collected in the fieldwork stage, and by extrapolating this information to other areas that were not visited but present similar spectral and visual characteristics. The raster map obtained as a result of the classification was filtered using a majority type of filter to smooth the class boundaries (Figure 3.7).

The statistics of the training samples defined for the land cover classes are presented in Figure 3.8. As in the previous classification of the sum normalized bands, the land cover classes “Forest and River-side Vegetation”, and “Dense Bush and Grass” present a different spectral response in all three principal components. This fact suggest that a clear differentiation and separability can be established among them. A very similar spectral response of areas classified as “Agricultural Land”, “Eroded land”, “Bare Soil for Agriculture” and “Sparse Vegetation” was observed specially in principal components 1 and 3. Then, this two principal components seems to be not very useful to differentiate the described land cover types. In the case of principal component 2, the classes “Eroded Land” and “Bare Soil for Agriculture” was observed specially in principal components 1 and 3. Then, this two principal components seems to be not very useful to differentiate the described land cover types. In the case of principal component 2, the classes “Eroded Land” and “Bare Soil for Agriculture” present a similar response. The same occurs for the “Agricultural Land” and “Sparse Vegetation”.

The feature spaces of the principal components combinations is presented in Figure 3.9. It can be observed that the clusters for the classes forest and river side vegetation and dense bush and grass do not present much overlap among themselves. This fact confirms the class separability introduced above. The rest of the classes present high overlap and hardly any differentiation can be observed, which introduces a limitation to map the eroded areas with the analysis of individual principal components.
3.5. Image classification

Figure 3.7: Classified image generated by the color composite of principal components 1,2,3 in RGB of sum normalized Landsat image.

Figure 3.8: Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite obtained from the principal components 123 in RGB, respectively, of sum normalized Landsat image bands.
3.5. Image classification

3.5.2 Classification of VNIR ASTER bands

The same land cover classes defined to classify the Landsat images were used to classify the false color composite generated with the VNIR ASTER bands. The training sample process and the selection of the classification algorithm were performed following the same criteria as explained in Section 3.5.1.

The raster map obtained as a result of the classification was filtered using a majority filter to smooth the class boundaries. It is presented in Figure 3.10.

The statistics of the training samples defined for the land cover classes are presented in Figure 3.11. The obtained values for bands 1 and 3 suggest a high separability among all the land cover classes defined. In the case of the VNIR band 2, a quite similar spectral response was obtained for the majority of the classes, except for the “Bare Soil for Agriculture”. This type of land cover is characterized for presenting the highest DN in all three bands, which permits a clear spectral identification.

The feature spaces of the individual bands are presented in Figure 3.12. It can be observed that most of the clusters for individual classes do not present a high overlap among themselves, except for the land cover classes “Agricultural Land” and “Sparse Vegetation”. From the feature space of band 2 and band 3, it can be observed that sharp class separation between the “Forest and River-side Vegetation” and the class “Dense Bush and Grass” cover is presented, as well as for the classes “Eroded Land” and “Bare Soil for Agriculture”.

3.5.3 Additional comments on image classification

An accuracy assessment of each classified image was carried out. For this, 73 points among the different land cover classes that correspond to field observations and areas
3.5. Image classification

Figure 3.10: Classified ASTER image

Figure 3.11: Bar chart with mean DN values of sampled pixels for the land cover classes identified in the classified color composite created from ASTER bands 321 in RGB, respectively.
3.5. Image classification

Figure 3.12: Feature spaces of classified ASTER image

with similar spectral characteristics, that were not used during the “training process” were used to validate the classification. For each classified image, a confusion matrix was constructed. It provides the correct and incorrect classified pixels, as well as the accuracy and reliability for each class.

Tables 3.5, 3.6, 3.7 present the confusion matrices obtained for the classified satellite images. The land cover classes “Forest and River-side Vegetation”, “Dense Bush and Grass Cover” and “Bare Soil for Agriculture” present a relatively high percentage of accuracy (more than 80%) in the three images; except for the last class in the sum normalized principal components of the Landsat image. This suggest a good spectral separability for these particular classes, as it was described in the previous section, where the bar charts obtained from the classification statistics were presented.

Table 3.5: Confusion matrix of the classified sum normalized Landsat image, bands 4,5,1.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>A</th>
<th>DBG</th>
<th>F</th>
<th>BSA</th>
<th>E</th>
<th>SV</th>
<th>Row Total</th>
<th>E. Comission (%)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>7</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>DBG</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>FRV</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>BSA</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>12</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>SV</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>8</td>
<td>16</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Col. Total</td>
<td>3</td>
<td>18</td>
<td>12</td>
<td>7</td>
<td>23</td>
<td>10</td>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. Omission (%)</td>
<td>100</td>
<td>22</td>
<td>0</td>
<td>14</td>
<td>65</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
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<td>78</td>
<td>100</td>
<td>86</td>
<td>35</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The classes “Eroded Land” and “Sparse Vegetation” present low to moderate levels of accuracy. In the case of the ASTER image, both classes were predicted with the lowest accuracy, 33% and 50%, respectively. For the sum normalized bands 4,5 and 1 of Landsat, the accuracy obtained was moderate for the “Eroded Land”, with 67% and low for the “Sparse Vegetation” with 50%. The opposite happened for the sum normalized principal components 1,2 and 3 of Landsat. The association of areas covered by sparse vegetation with morphodynamic processes like sheet, rill and gully
3.5. Image classification

Table 3.6: Confusion matrix of the classified sum normalized Landsat image, principal components 1,2,3.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>A</th>
<th>DBG</th>
<th>F</th>
<th>BSA</th>
<th>E</th>
<th>SV</th>
<th>Row Total</th>
<th>E. Comission (%)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>0</td>
<td>3</td>
<td>7</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>DBG</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>14</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>BSA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>3</td>
<td>12</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>SV</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>16</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>Col. Total</td>
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<td>12</td>
<td>10</td>
<td>11</td>
<td>18</td>
<td>73</td>
<td></td>
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<tr>
<td>E. Omission (%)</td>
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<td>0</td>
<td>0</td>
<td>10</td>
<td>45</td>
<td>33</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Reliability</td>
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<td>90</td>
<td>55</td>
<td>67</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7: Confusion matrix of the classified false color composite ASTER image, bands 3,2,1.

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>A</th>
<th>DBG</th>
<th>F</th>
<th>BSA</th>
<th>E</th>
<th>SV</th>
<th>Row Total</th>
<th>E. Comission (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>DBG</td>
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erosion represents a major difficulty to differentiate both categories even with the higher spatial resolution of ASTER. The spectral mixture of these two classes can be high and then more sophisticated techniques like spectral un-mixing, [27], could be an approach that would permit their differentiation.

The class “Agricultural Land” presented a special situation in the case of the sum normalized band 4, 5 and 1 of Landsat. None of the seven selected points to assess the accuracy of the classification were correctly classified. Six of them were classified as “Eroded Land” and one as “Sparse Vegetation”. In the sum normalized principal components 1,2 and 3 of Landsat, the accuracy obtained for this class was 43%. The most common types of crops that are present in the study area are olives and almonds. They are cultivated in such a way that the spacing between lines of almond and olive trees are approximately 2 to 3 m. This also presents a problem for the identification of agricultural areas with the spatial resolution of Landsat. This class was predicted with an accuracy of 86% with ASTER.

The following paragraphs present two examples of corrected and misclassified areas. A land cover map was overlaid to the satellite images and a morphodynamic process map are included in the analysis. These maps were added to the ILWIS “pixel information window” to visualize the class assigned to the selected pixels.
3.5. Image classification

Figure 3.13: Insets of classified Landsat and ASTER images.

Figure 3.13 shows a case of a successful classification in the Landsat sum normalized bands 4, 5 and 1 and ASTER images for the class “Dense Bush and Grass”. The question mark in the morphodynamic processes map represents the absence of erosion or solution processes. The association of this particular land cover class with non-eroded areas was well established during the visual image interpretation and verified with fieldwork observations. The results for the sum normalized principal components 1, 2 and 3 of the Landsat correspond to a misclassification of this land cover type as it is represented as “Eroded Land”.

A comparison of the upper-right corner of the images shows that in the Landsat sum normalized bands 4, 5 and 1 a high percentage corresponds to “Eroded Land” and for the Landsat sum normalized principal components 1, 2, 3 and the ASTER images the areas are classified as “Agricultural Land” and “Sparse Vegetation”. This example illustrates what was represented in the accuracy assessment for the Landsat sum normalized bands 4, 5 and 1, where the class “Agricultural Land” was completely misclassified.

The second example is presented in Figure 3.14. This corresponds to a successful classification for the land cover class “Bare Soil for Agriculture” as it is shown in the ILWIS pixel information window. The two Landsat images present a similar distribution for this class and some areas in the ASTER image belong to the classes “Sparse Vegetation” and “Eroded Land”; both classes are closely related as they indicate the presence of morphodynamic processes. The class “Dense Bush and Grass Cover” has a similar distribution in the principal components of Landsat and ASTER images.

The next step to be considered is the improvement of the obtained classifications. For this, the information in the feature spaces of the classified images could be used
3.6 Conclusions

The contribution of remote sensing to map the spatial distribution of the land cover types focusing on the identification of erosion-related classes has been “partially” illustrated in this chapter. Different approaches, methods, techniques and sensors were tested in the Tabernas study area to explore their potentials and limitations to map the land cover types associated with land degradation features.

- This chapter have dealt only with the study of satellite remote sensing (Landsat and ASTER imagery) and basically three approaches of image enhancement were followed (sum normalization, principal component analysis and color composite generation), prior to the image classification.

- The resultant maps showing the spatial distribution of different land cover classes were obtained by visual and digital interpretation and classification on the

Figure 3.14: Insets of classified Landsat and ASTER images.

...to reclassify them. The analysis of the shape and size of the clusters in each feature space would permit to define the appropriate spectral ranges to represent each thematic class. This step can lead to the re-definition of the thematic classes and finally an improved classified product can be obtained. The use of spectral unmixing techniques [27] would also improve the obtained classifications.

It was presented in Sections 3.5.1 and 3.5.2 that some individual bands enhanced the spectral differences among different land cover classes. This fact could be used to carry out supervised classifications on those individual bands e.g., the near infrared band 3 of ASTER, and the same spectral range for the sum normalized Landsat band 4, to improve the obtained results.

3.6 Conclusions

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3.6. Conclusions

enhanced images. The visual interpretation as well as the information collected in the field became extremely important and it was used to select the “training samples” for image classification. During the fieldwork, the identification of terrain patterns (bare soil surfaces, gullied and areas covered by sparse vegetation) helped to recognize land degradation features in the images. In this study, it has been shown once more the importance of integrating field observations with remotely sensed data, as an approach to produce thematic information in the earth sciences.

- The land cover classes “Forest and Riverside Vegetation”, “Dense Bush and Grass” and “Bare Soil for Agriculture” were predicted with high accuracy in the Landsat and ASTER images. The classes “Eroded Land” and “Sparse Vegetation” presented a low to moderate level of accuracy. The class “Agricultural Land” was well detected with ASTER, low accuracy was obtained for the Landsat sum normalized principal components 1, 2 and 3, and a total misclassification was obtained for the Landsat sum normalized bands 4, 5 and 1.

- Reclassification of appropriate individual bands, in which the spectral differences among the land cover types are significant, considering the shape and size of the clusters for individual classes in the feature spaces would be useful to improve the classification. The use of other techniques that consider the spectral mixture of pixels can be performed to improve misclassifications.

- ASTER with its higher spatial resolution in the VNIR spectral range, the possibilities of stereo vision and the generation of DEM in Band 3; offers more advantages for specific applications e.g. geomorphologic mapping, than Landsat imagery. Also, the broad spectral resolution for the SWIR and TIR ASTER images, represents an important advance that permits to undertake a wide variety of applications in the earth and related sciences. The possibility to obtain ASTER datasets “free of charge” makes the ASTER sensor more attractive than Landsat. Among the constraints that pose a limitation for ASTER, compared with Landsat, is the necessity of specialized software to handle the original “hdf” format files that the EOS-GDS provide, the availability of geometrically and radiometrically corrected 1B products and the necessity to develop computer programs that permit to transform 1A to 1B products.
Chapter 4

Geomorphological Mapping to Assess Morphodynamic Processes as an Indicator of Land Degradation

4.1 Introduction

This chapter describes results obtained in the geomorphologic mapping and multi-temporal aerial photograph interpretation to assess the morphodynamic processes. First, the general characteristics of the different geomorphic mapping systems, including the terrain mapping unit approach that will be followed in this work; and the information derived from it, are presented. This is followed by the characterization of the geomorphologic units, including the morphogenetic and morphometric terrain elements. Finally, an introductory definition of the different morphodynamic processes affecting the area of Tabernas is a preamble to present the multi-temporal image interpretation that supports the geomorphologic mapping.

4.2 Terrain Mapping Unit Approach

Geomorphology is a science whose main objective is to explain the origin (morphogenesis) and evolution (morphodynamics) of the landscape. Different terrain classification systems have been developed to assess the geomorphologic and other terrain aspects (geology, processes, soils, land use and land cover). Those systems follow relatively different approaches and the common idea is the hierarchical division of the terrain elements as a function of the scale of mapping.

One of the first attempts to propose a terrain classification system, was the methodology for land evaluation of the C.S.I.R.O (Commonwealth Scientific and Industrial Research Organization) in Australia [15]. It was developed during the Second World War between 1943 and 1945. It is based in a physionomic and physiographic landscape characterization. There are three hierarchical levels for characterization
of morphologic aspects of the terrain: land systems, land units and land facies.

The ITC system of geomorphologic survey, terrain analysis and classification [72], [73] and [79] is based on a landscape approach where the main characteristics are the recognition, description and hierarchically division of terrain features and elements (relief, geomorphic processes, rock, soil and hydrologic characteristics), using aerial photographs, space imagery and fieldwork observations. According to the scale of mapping, four hierarchical levels are defined: terrain provinces, systems, units and terrain components. The application of each one of the methods depends on the purpose of geomorphologic mapping, it can be either general or applied.

The terrain mapping unit approach [42] is an adaptation of the ITC classification system and will be implemented and adapted here to interpret the geomorphology of the Tabernas area. It is based on the systematic input of natural terrain aspects (geomorphology, lithology, morphometry and soils) into a database of a geographic information system. Some of the most important characteristics of this approach are:

- It is simple and flexible;
- Quantitative, parametric or statistical descriptions of relief, drainage and slopes are incorporated in the classification;
- Capture of the terrain data in a format, which allows processing as generalization, extrapolation and statistical analysis.

4.3 Description of the Geomorphologic Units in the Study Area

The description of the geomorphologic units has been based on the interpretation of aerial ortho-photo mosaics, Landsat and ASTER imagery, and on the data collected in the fieldwork stage that were used to produce the geomorphologic map of the study area Figure 4.1. A systematic description will be presented following the terrain mapping unit approach, where morphologic and morphometric features (extracted from a Digital Elevation Model, DEM) will be used to describe each geomorphologic unit.

As it was described in Chapter 2, two physiographic units can be differentiated in the study area, Basement Mountains and Neogene and Quaternary sedimentary cover. The numbers used here to label the geomorphologic units correspond to a physiographic and geomorphologic classification. The first number refers to the physiographic units (1) for Basement Mountains and (2) for Neogene and Quaternary sedimentary cover. The second number corresponds to each geomorphologic unit, which will be characterized in terms of:

- Geographic location and extension;
- Altitude range;
- Lithology;
- Shape and length of water dividers;
4.3. Description of the Geomorphologic Units in the Study Area

Figure 4.1: Map of geomorphologic units of the Tabernas area.

- Drainage pattern, density and relative degree of dissection;
- Internal relief;
- Morphodynamic processes;
- Soils;
- Land cover;

The morphometric data, e.g., slope inclination, aspect, shape, altitude range and internal relief were derived from a DEM with 25 m resolution. The DEM was sliced using ILWIS 3.0 according to different classes defined for the morphometric thematic maps. Then, statistical information was extracted by overlaying them with the map of geomorphologic units to complete their characterization. Also, a shadow map was derived from the DEM and became very important to support the image interpretation stage to define some of the boundaries of the geomorphologic units. All the thematic information, which consists in maps and attribute tables used to describe the geomorphologic units, was incorporated in the spatial database processed with the geographic information system.
4.3. Description of the Geomorphologic Units in the Study Area

4.3.1 Geomorphologic units of the basement mountains

Three geomorphologic units were identified in the physiographic unit named Basement Mountains, where the terrain morphology corresponds to mountainous areas with steep relief. A description of the morphologic and morphometric aspects follows.

**Moderate relief of the Sierra de Los Filabres (U1.1)**

This unit is located in the northern part of the study area and presents an extension of 12749 Ha, which represents the 27.6%. It has an altitude range from 408 to 1158 m.a.s.l. The landforms are developed in graphitic schists at the western side and quartz feldspathic schists at the eastern side. Due to the strong foliation exhibited by these rocks, which controls the topographic features, the relief can be classified as structural-denudational (Figure 4.2). The water dividers are narrow and elongated predominantly in the N-S to the NW-SE directions.

![Figure 4.2: Panoramic view of the Sierra de Los Filabres (at the background), with strong structural control visible in the water divider shape and orientation. Limestone hills in the middle of the photograph are surrounded by an undulating relief of recent deposits.](image)

The slopes present convex (42%) and concave (41%) shapes and face towards the south-east. Nearly 50% of the unit presents steep slopes, predominantly those developed in graphitic schists; and 25% present moderately tilted slopes. The drainage pattern is parallel to subparallel with moderate density and high dissection predominantly in a north–south direction.

The morphodynamic activity is not too strong along the unit, but a zone of active gully erosion is presented at the north of the Almería Solar Plant, located close to the road from Tabernas to Velefique. Rock falls are observed in places where the slopes are very steep.

The soil development is very scarce and rocky outcrops dominate the unit. The most common soil types are Eutric and Calcaric Regosol. The land cover is represented by moderately dense herbaceous vegetation.
4.3. Description of the Geomorphologic Units

in the Study Area

Moderate relief of the Sierra Alhamilla (U1.2)

It is located in the north-western margin of the Sierra Alhamilla and covers an area of 968 Ha, which corresponds to 2% of the total area. The altitude ranges from 408 to 883 m.a.s.l. It is composed by phyllites and marbles of the Alpujarride Complex. The water dividers are moderately wide and elongated in a north-south direction. The relief is highly controlled by the lithology, rough where the marbles outcrop and moderate where the phyllites are present.

The slopes present concave (44%) and convex (42%) shapes. They face predominantly towards the north-west (43%) and the north-east (30%). Almost 80% of the unit presents slopes which range between moderately tilted to steep slopes, the latter ones occupy 58% of the total area of the unit. The drainage pattern is subparallel to subdendritic with moderate density and dissection, predominantly in a south–north direction.

As in the whole study area, in the Sierra Alhamilla the morphodynamic processes are strongly controlled by the lithology. In the phyllites small patches of rill and sheet erosion can be identified. Scars of old inactive landslides were observed during the field survey.

The soils developed in this unit correspond in a great extent to Calcaric Regosol. The most dominant land cover type is represented by dense bush and grass cover and areas of sparse vegetation which are highly susceptible to host the described morphodynamic processes.

Steep relief of the Sierra Alhamilla (U1.3)

It is located in the south-eastern part of the study area and covers an extension of 3951 Ha, which corresponds to nearly 9%. The altitude ranges from 532 to 1214 m.a.s.l. The morphologic expression of this unit corresponds to mountainous areas developed in graphitic schists of the Nevado Filabride Complex, and phyllites and marbles of the Alpujarride Complex. The outcrops of marble are characterized for forming rocky scarps, which is a distinctive feature of this part of the Sierra Alhamilla (Figure 4.3). This unit presents narrow and sharp water dividers predominantly, but there are also small areas specially occupied by phyllite outcrops that present wider and subrounded dividers.

The most predominant slope shapes are convex (42%) and concave (40%), the rest 18% of the unit presents straight slopes. Almost 65% of the terrain presents slopes facing the north-east and the north-west direction. Most of the unit presents steep slopes (60%) and a 22% has moderately tilted slopes. The drainage pattern is subparallel with moderate to high density and the dissection of the unit is high, especially in the eastern part.

Few areas of sheet erosion, where the original land cover had been removed, represent the most important morphodynamic process affecting this unit. Small areas of rill and gully erosion, developed mainly in phyllites were also identified during the fieldwork (Figure 4.4). In some cases they are associated to road construction as will be described in the next chapter.

Signs of instability can be identified by the presence of ancient and dormant landslides in the vicinity of the municipality of Turrillas and areas used for previous
4.3. Description of the Geomorphologic Units in the Study Area

Figure 4.3: Areas of steep relief (scarps in marbles) in the Sierra Alhamilla in the vicinity of Lucainena de las Torres, at the bottom a lower relief in Tertiary sediments.

mining activities between Turrillas and Lucainena de las Torres. Debris flows can be observed in the road cuts to the television tower that is located in the uppermost part of the Sierra Alhamilla. These deposits are composed by angular rock fragments immerse in a sandy matrix. They are unconsolidated materials that reflect some degree of soil creep by the presence of pine trees tilted in the sense of the slope. Rock falls specially in the scarps of the marbles are also present. The soils in this unit are dominantly of Calcaric Regosol type.

4.3.2 Geomorphologic units of the Neogene sedimentary and Quaternary cover

Ten geomorphologic units were identified in this physiographic unit. The relief is characterized by a low altitude and it is in this region where most of the human activities take place. It will be described in the next chapter. A description of the main characteristics of the relief in this unit follows.

East-west elongated low ridges (U2.1)

This unit is located in the south-central part of the study area and covers 1780 Ha, that represents nearly 4% of the total area. The altitude ranges from 358 to 728 m.a.s.l. As the name indicates, the morphology is represented by low hilly ridges elongated in an east–west direction. The western ridge, known as “Serrata del Marchante” is controlled by an antiform structure resulting from the folding of Tortonian conglomerates. The other ridges are formed by thinner bodies of limestones, marls and sandstones. The water dividers are sharp and coincide with the axes of the anticline in the case of the western ridge (Figure 4.5).

There is no predominant slope shape. The convex slopes represent the 35%,
4.3. Description of the Geomorphologic Units in the Study Area

Figure 4.4: Rills developed in phyllites in the Sierra Alhamilla near Lucainena de Las Torres.

Figure 4.5: View of the 'Serrata del Marchante' and of the areas of undulating relief showing a contrasting morphology.

concave ones the 34% and the straight ones the 30%. Regarding the facing direction, in 60% of the area the slopes face to the south-east and south-west and the remaining 40% faces towards the north-east and north-west. The inclination is also variable, the steep slopes occupy 40% of the area; the rest presents slopes ranging from gentle to moderately tilted. The drainage pattern is parallel with moderate density and low dissection with a dominant north-south direction.

Sheet and rill erosion were identified as the main morphodynamic processes that affect this unit. Particularly, as will be presented in Chapter 5, the type of lithology and some changes in the land cover pattern are the main causes to the development of the mentioned processes. Even though it is difficult to detect and quantify them, given the scale of work and the resolution of the available data, some morphologic changes that have taken place in this unit were observed during the fieldwork. They are of anthropogenic origin due to the levelling of the terrain to prepare the soil for agricultural practices (particularly extensive olive plantations).

This unit presents a high heterogeneity of soil types. The most predominant ones
4.3 Description of the Geomorphologic Units in the Study Area

are Calcaric Lithosols. The dominant land cover type is dense bush and grass but there are areas of bare soil and sparse vegetation, as well as areas of agricultural use.

**Limestone hills (U2.2)**

The limestone bodies are located in the north-eastern part of the study area and have an extension of 1465 Ha, which represents nearly the 3\%. The relief is very low and this unit is found at altitudes from 506 to 750 m.a.s.l. Morphologically, the unit is formed by rounded hills (Figure 4.2) following an east-west direction, controlled by the bedding of the limestones. The dividers are very wide and rounded, and particular landforms such as dolines, and hills of conic shape are observed in the area.

The most predominant slope shape is straight (46\%) and convex and concave slopes occupy 27\% and 26\%, respectively. Two common directions of slope facing are found towards the south-east and south-west. The inclination of the terrain ranges from gentle to steep slopes. The drainage pattern is dendritic with moderate density and dissection.

Due to the nature of the parent materials, solution is the most common geomorphologic process. Small solution holes can be found in the outcrops as a small scale indication of the presence of this process. Because of the dry semi-arid to arid climate that characterizes the Tabernas area, the result of the solution process is not reflected in an extensive development of a karstic landscape, even though landforms such as the ones mentioned above can be seen.

As the nature of the parent materials is calcareous, the Calcaric Regosol is the most common soil type of the unit. The land cover is mainly composed of dense herbaceous vegetation.

**Gypsum hills (U2.3)**

Three gypsum bodies are found in the study area. Two in the central-eastern part and one immerge in the badlands, in the western side. The extension of this units occupies 578 Ha that corresponds to 1.25\% of the total area. Morphologically, this unit corresponds to low hills. This unit presents an altitude range from 379 to 649 m.a.s.l. The water dividers are wide and short.

The most predominant slope shape of this unit is straight (40\%), concave and convex slopes occupy the rest of the area with individual extension of 30\% each. The slope inclination presents a wide variety of ranges, the central-eastern bodies have more gentle slopes and the western body is characterized by steeper ones. The drainage pattern is subdendritic with low to moderate density and low dissection.

Morphodynamic processes like sheet erosion and solution features, such as sinkholes, affect this unit. Two soil types are developed in this unit. The Vermic Gypsisol predominates over the Calcaric Regosol. The most common land cover types are sparse bush and herbaceous vegetation.
4.3. Description of the Geomorphologic Units in the Study Area

**Isolated hills (U2.4)**

This unit is located in the central part of the area and has the lowest extension among all the geomorphologic units with 284 Ha, which corresponds the 0.6% of the study area. It is found at altitudes from 355 to 687 m.a.s.l. It is composed of low, isolated remnant hills formed in graphitic schists and conglomerates. The water dividers are subrounded and narrow in the hills developed in metamorphic rocks and rounded and wide in the hills of sedimentary rocks.

The most predominant slope shape is straight with 68% of the unit area, and the facing direction is towards the south-east (43%). The inclination is generally gentle (43%), but also tilted to moderately tilted slopes occupy 42%. The 12% of the unit presents steep slopes. The drainage pattern is sub-parallel with low density and dissection.

Surface processes like sheet and rill erosion are commonly found, especially where the bare soil is the main land cover type. Two soil types are developed in this unit, Eutric Fluvisol and Calcaric Regosol. The most characteristic land cover types are sparse vegetation and bare soil.

**Badlands (U2.5)**

This unit is located in the south-western part and presents an extension of 5540 Ha, which corresponds to 12% of the study area. The altitude ranges from 220 to 660 m.a.s.l. Morphologically it is composed of intermediate to low hills developed in soft marls, sandstones and conglomerates. Besides the lithology, the morphology is controlled in a great extent by the structure (bedding planes), leading to the formation of hogs backs and cuestas in the hills. As a consequence, long, narrow and sharp dividers are commonly found (Figure 4.6).

![Figure 4.6: Panoramic view of the badlands of Tabernas, the strong morphodynamic activity and the characteristic morphology are distinctive features of this unit.](image-url)
4.3. Description of the Geomorphologic Units in the Study Area

The slopes present concave (42\%) and convex surfaces (41\%) and face towards the south-east and to the south-west. The inclination is not homogeneous, 61\% of the terrain is in the range between moderately tilted to steep slopes and nearly 30\% has gentle to tilted slopes. The drainage pattern is subdendritic with high density and dissection.

The most characteristic morphodynamic processes that affects this unit are rill and sheet erosion, which in more advanced stages results in severe gully and sheet erosion (Figure 4.6).

The soils in the badlands belong to the Orthic Solonchak type. The land cover is represented by sparse herbaceous vegetation, bare soil surfaces and is also common to find desert pavements characterized by small rocky fragments of quartzitic composition distributed on top and at the base of individual hills and ridges.

**Low hills (U2.6)**

This geomorphologic unit is distributed in the south-central part, between the Sierra Alhamilla and the East-west Elongated Low Ridges; and the eastern part of the study area. It has an extension of 6672 Ha, which corresponds to the 14\%. The altitude ranges from 379 to 771 m.a.s.l. The most common morphologic feature of this unit are hills of very low altitude and an undulating relief. The water dividers are wide and rounded (Figure 4.5 and Figure 4.3). The lithology is constituted by marls, sandstones and conglomerates.

The 66\% of the unit presents straight slopes, which face in almost all directions with out a preferable orientation. The inclination is low with 44\% of the area presenting gentle slopes and 28\% being tilted. The drainage pattern can be classified as sub-parallel with low density and dissection.

The most common morphodynamic process is sheet erosion, specially developed in areas of bare soil. Areas of sheet and rill erosion were also observed particularly associated with areas of sparse vegetation cover. The Calcaric Regosol is the most common soil type that is developed in this unit.

**Peneplanation surfaces (U2.7)**

They are widely distributed in the study area in patches of small extension. In total, they cover 1423 Ha, which corresponds to 3\%. These surfaces can be found at altitudes between 301 and 676 m.a.s.l. The morphology corresponds to flat horizontal and inclined surfaces of Plio-Pleistocene alluvial terraces and colluvial deposits, that cover older sedimentary rocks. They are composed of gravels and sands with horizontal to sub-horizontal stratification, in most cases the top most layer consists of highly cemented calcareous conglomerates. Three different levels of peneplanation surfaces were recognized in the field survey, corresponding to different stages of erosion and deposition (Figure 4.7). The the neotectonic activity has also influenced these differences in height and tilting of individual surfaces.

The predominant slope shape is straight and there is not a characteristic facing direction. The inclination varies from completely horizontal to moderately tilted. The drainage pattern is parallel with low density and very low to high dissection due to gully development in some of the alluvial terraces.
4.3. Description of the Geomorphologic Units in the Study Area

Figure 4.7: Three different levels of peneplanation surfaces can be recognized in the photograph, at the background is the geomorphologic unit "Moderate Relief of Sierra Alhamilla".

As described above, gully erosion is a process common to some of these surfaces. As a result of slope retreat by incision of the stream channels developed in soft materials and covered by the peneplanation surfaces, rock falls is another common process associated with them. Sheet erosion was also observed at the top part of some surfaces specially where there is no vegetation covering them.

Two predominant soil types are developed in this unit. They correspond to Calcareic Regosol and Orthic Solonchak. The land cover is generally composed by grass.

Alluvial fans (U2.8)

They occupy the central portion of the study area and have an extension of 6867 Ha, which corresponds to approximately 15% of it. The altitude ranges from 362 to 838 m.a.s.l. The morphology is represented by flat to undulating surfaces formed by Quaternary deposits like gravels and sands dominantly coming from the Sierra de Los Filabres, but also from the Sierra Alhamilla.

The slope shape is mostly straight (82%) and facing towards the south-east and south-west. The fans generated from debris flow coming from the Sierra Alhamilla present slopes facing towards the north-east and north west. The inclination is predominantly gentle, covering 68% of the area. The drainage is mostly surficial with scarce development. According to the internal relief classification for the Tabernas area, this unit belongs to the flat class.

The development of processes such as sheet, gully and rill erosion followed the stage of deposition of these alluvial fans. The soils found in these deposits belong to the Eutric Fluvisol type. The land cover is dominantly herbaceous vegetation with areas for seasonal cultivation and dry farming.

Alluvial terraces (U2.9)

This unit covers small parts in the central and southwestern part of the study area and has an extension of 449 Ha, which corresponds to nearly 1% of it. They are found at altitudes ranging from 226 to 503 m.a.s.l. The alluvial terraces correspond
4.4. Geomorphologic Processes and Associated Landforms

to flat horizontal surfaces of conglomerates and sands without bedding.

The slope shape is predominantly straight and gentle. The facing direction does not have any particular trend and ranges from the south-east (27%), south-west (26%) and north-west (25%). There is no development of drainage pattern, which indicates that these deposits have recently been formed.

The scarce drainage development of this unit is associated with morphodynamic processes acting as a consequence of slope retreat. Rill and gully erosion are affecting this unit and some terraces present in the top part areas of sheet erosion. The soils correspond to Calcaric Fluvisol. The land cover is mainly herbaceous vegetation with areas of bare soil.

Alluvial plains (U2.10)

They are located in various parts of the study area and cover an extension of 1766 Ha, which corresponds to approximately the 4%. The alluvial plains are present with an altitude ranging from 256 to 916 m.a.s.l. Morphologically they correspond to flat surfaces, separated by scarps from the alluvial terraces and the sedimentary sequences; some of them are wide and others are just restricted to a few meters and can not be represented in the geomorphologic map. Those that are wider are called “ramblas”. It is common to find landforms like central and lateral bars. They are composed by unconsolidated gravels and sands, which corresponds to the most recent alluvial deposits.

The slope shape is predominantly straight without any particular facing direction. The inclination is mostly gentle (83%) and tilted (9%). They constitute the actual drainage configuration, the main “ramblas” exhibit a braided drainage pattern with multiple channels that are permanently dry. The most common morphodynamic process observed is lateral erosion of the walls of the drainage, even though it is not a severe process due to the particular climatic conditions of the area.

The soils are Calcaric Regosol and the dominant land cover is bare soil and herbaceous vegetation in the oldest alluvial bars.

4.4 Geomorphologic Processes and Associated Landforms

This section describes the morphodynamic processes identified in the study area as a result of multi-temporal image interpretation and fieldwork survey. The term morphodynamic process is used here to make reference to those natural processes resulting from erosion or solution that produce a change in the landforms and consequently influence the landscape development.

As erosional processes can be considered those where the principal origin is the detachment of individual soil particles by the action of raindrops with a subsequent movement downslope. They can be subdivided into two categories: surficial and concentrated erosion processes. **Surficial** erosion processes are formed mainly by the action of laminar flow or wind, sheet erosion is the most representative example of this type of processes. **Concentrated** erosion processes are those where the flow
conditions are higher. This conditions result in rill and gully formation. However, in some areas surficial and concentrated processes can be present together; or as a result of surficial processes acting on landforms, a subsequent stage of generation of concentrated processes influence the landform development. The landforms associated with the erosion processes are the increasing of shape and size of stream channels and accumulation of sediments at the bottom of the valleys, foothills or tophills, like in the desert pavements formation.

The solution processes refer to those generated by the action of chemical and biological weathering of rocks with soluble components, such as carbonates and gypsum. As a result of solution processes the landscape develops negative landforms, that consist of sinkholes or dolines and positive or conic landforms.

A brief description of the morphodynamic processes considered and the parameters used to identify them during the image interpretation and fieldwork stages in the Tabernas area is presented in the following paragraphs.

- **Sheet erosion**: This is a type of surficial process that is developed specifically when the soil loses its vegetative cover and is exposed to the atmospheric agents such as raindrops. It consists in the detachment of individual soil particles and further accumulation in a place different of its origin but generally close to it (Figure 4.8). In the aerial photographs, sheet erosion was identified basically by the tonal and textural variations. Eroded areas appeared in lighter tones and mottled texture, while non-eroded areas appeared in darker tones depending on the particular land cover type. In the satellite images, areas of sheet erosion were recognized also by patches with high reflectance. This criteria was very useful to differentiate the bare soil from other types of land cover.

- **Rill erosion**: Rills are terrain features that consist of small channels, generally of few centimeters wide and deep (maximum 50 cm), resulting from concentrated flow processes (Figure 4.4). Their dimensions have been established
4.4. Geomorphologic Processes and Associated Landforms

Fig 4.9: Gullies developed in soft marls in the Tabernas badlands area.

arbitrarily [8] and are controlled by the erodibility of the soil. Usually fine grained soils are more erodible than coarser soils [72]. In more advanced stages of development, rills can form small individual valleys and when the erosional power of the current increases, the valleys become connected and develop gullies. Areas of rill erosion where identified much better in the aerial photographs rather than the satellite images due to their higher spatial resolution. The criteria used to define rills in the aerial photographs were a qualitative evaluation of rill depth, areas of high drainage density and the condition of the vegetation, commonly associated with areas of sparse vegetation and a more intense stage of erosion than the areas dominated by sheet erosion.

• **Gully erosion**: Gully as well as rill erosion are complex morphodynamic processes that characterize areas of concentrated erosion (Figure 4.9). Gullies have been defined from different perspectives, e.g. agricultural, and landscape. From the former, they are considered as stream channels whose width and depth do not allow normal tillage [20] in [8]. From a landscape perspective, gullies are defined as steep-sided eroding water courses that are subject to ephemeral flash floods during rain storms [44] and [29] in [8]. They have been associated with accelerated anthropogenic erosion processes and with landscape instability; identified also as transgression of geomorphologic thresholds (extrinsic and intrinsic to the gully system itself) [60]. In the area of Tabernas both influences can be appreciated, prevailing the natural conditions and susceptibility of the parent materials. This aspect will be discussed later on in the next chapter.

The elements of aerial photograph interpretation used to identify gullied areas are similar to those used in the identification of areas affected by rill erosion. The differences were basically morphological due to the fact that the gullies identified were characterized as a later state in the development of rills. Then, light tones, and extremely high drainage density observed as a special shape and pattern of the terrain; were the main elements used to identify gullied
4.4. Geomorphologic Processes and Associated Landforms

areas.

- **Solution processes**: In the study area, solution processes were identified and associated with particular lithologic units, like limestone and to a lesser extent with gypsum rocks. They were recognized in the image interpretation stage by the morphological expression of the landscape and in the fieldwork, besides the last criteria, by outcrop inspection. Characteristic morphologies such as dolines and small scale sinkholes as well as isolated hills with conic shape are the most common landforms that indicate the development of a karstic landscape. In the Tabernas area, this type of landscape is not well developed due to the climatic conditions of a semi-arid to arid environment.

The recognition, description and characterization of the morphodynamic processes in the field was an important input to identify the effects of geomorphologic activity in the multi-temporal image interpretation stage. The extrapolation of particular features and sites identified in the field to recognize different processes in the last set of aerial photographs (1995) and recent ASTER images has resulted in a key parameter to identify the individual processes in the previous sets of aerial photographs, corresponding to the years 1956 and 1981.

There were some constraints in the interpretation of the different ortho-photo mosaics to identify particular morphodynamic processes, such as sheet erosion. Basically, they consisted in the tonal variations among the three different periods of acquisition. In particular, the differences presented in those photographs that were not acquired the same day that the rest of the photographs that belong to the same ortho-photo mosaic (1956).

Also, due to the changes in the land use and land cover pattern that have occurred in the area, patches that at a certain time had a specific type of cover, presented different tones in more recent years. As an example, areas that were prepared for agricultural activities in the past, presented at that particular time a high reflectance due to the bare soil cover. Then, in more recent years, they were occupied by a certain type of crop, hence, the reflectance of the same patch decreased. This type of situation created some degree of difficulty in order to classify those areas and might have certain influence in the final results of the multi-temporal image interpretation.

The following sections present the description of the multi-temporal interpretation of the analog and digital aerial photographs supported by field observations to map the spatial distribution of the different morphodynamic processes.

### 4.4.1 Morphodynamic processes in 1956

As a result of the interpretation of the ortho-photo mosaic of the year 1956, 5831 Ha that correspond to 22.02% of the whole study area, were interpreted as affected by the different types of morphodynamic processes. Figure 4.10 shows the spatial distribution of the affected areas.

Areas of sheet erosion are widely distributed and cover nearly 10% of the study area. It was the most dominant process identified. Areas presenting a combination of rill and sheet erosion occupy 5% and represent the second category in area coverage. They consist mainly of one area in the foothills of the Sierra Alhamilla (Figure 4.8)
4.4. Geomorphologic Processes and Associated Landforms

Figure 4.10: Morphodynamic processes in the year 1956.

and a small patch at the foothills of the Sierra de Los Filabres. Areas affected by solution process are located in the northeastern part and occupy 2.81% of the total area. In the central-western margin, an zone was classified as presenting moderate to high sheet and rill erosion and occupies 1.16%. Areas of gully erosion present an extension of 1.37% of the total area and those of gully mixed with sheet erosion occupy only 0.1% in this particular year (Figure 4.11).

4.4.2 Morphodynamic processes in 1981

The interpretation of the ortho-photo mosaic of 1981 permitted the classification of the areas affected by morphodynamic processes. The spatial distribution of the affected areas for the year 1981 is presented in Figure 4.12. The evolution shows an increase from 5831 in 1956 to 6167.04 Ha in 1981 that represents 23.29% of the total area.

Figure 4.13 presents the extent (in percentage) of the affected areas in 1981. It was detected an increase of 76.52 Ha, with respect to 1956, in the areas affected by gully erosion, which corresponds to 0.29%. Areas of combination of rill and sheet erosion present an increase of 77.56 Ha, which corresponds to 0.3%. Areas affected by gully and sheet erosion show an increase of 27.88 Ha that represents 0.1%. An increase in the areas affected by rill erosion from 107.88 Ha in 1956 to 175.44 Ha in 1981, represents 0.25% of the total area.
4.4. Geomorphologic Processes and Associated Landforms

Figure 4.11: Extent of morphodynamic processes in the year 1956.

Figure 4.12: Morphodynamic processes in the year 1981.
4.4. Geomorphologic Processes and Associated Landforms

4.4.3 Morphodynamic processes in 1995

The interpretation of the ortho-photo mosaic of 1995 and the ASTER image permitted to classify the affected areas as well as their evolution through time, by comparing the results obtained in the interpretation for the years 1956 and 1981. The results of the spatial distribution of the morphodynamic processes are presented in Figure 4.14. The evolution shows an overall decrease from 6167.04 Ha in 1981 to 6156.6 Ha in 1995, that represents 10.44 Ha or 0.04\% less than the affected areas in 1981.

Figure 4.15 presents the percentage of the areas affected in 1995. Areas affected by a combination of rill and sheet erosion increased with respect to the year 1981 from 1410.84 Ha to 1731.64 Ha, which represents 1.21\%. The areas of a combination of gully and sheet erosion represent another high increase, from 0.2\% in 1981 to 3.36\%. It was interpreted as the evolution of areas that were classified in the previous two periods as presenting moderate to high sheet and rill erosion, and gully erosion. Two areas classified as presenting salinization were delineated in the photo interpretation based on the high reflectance and verified during the fieldwork stage. They cover an extension of 77.02 Ha that represent 0.29\% of the study area.

The time considered for the analysis of the morphodynamic processes, with nearly 50 years in aerial photograph coverage, is very short compared with the temporal scale of the geomorphologic time. The availability of data with a higher temporal resolution is a limitation in studies dealing with assessing changes in natural processes, like this one. The incorporation of long term climatic data is also an aspect that would permit a better characterization of the evolution of the different processes.

Regardless the previous constraints, the results obtained from the ortho-photo mosaics and space imagery interpretation show that certain dynamism exists in particular morphodynamic processes such as sheet, rill and gully erosion. This dynamism is considered in this work to a great extent as natural, according to the relationships established between the processes and the lithologic, geomorphologic and overall climatic conditions as will be described in Chapter 5. Nevertheless, due to modifications in the land use and land cover patterns, and road construction and de-
4.4. Geomorphologic Processes and Associated Landforms

Figure 4.14: Morphodynamic processes in the year 1995.

Figure 4.15: Extent of morphodynamic processes in the year 1995.
4.5 Conclusions

This chapter synthesizes the most relevant geomorphological aspects as a basis to the study of land degradation in the study area. The integration of remotely sensed imagery interpretation with field observations permitted the study of two main geomorphological aspects:

- The spatial representation and characterization of the different geomorphic units;
- The definition, identification, characterization and evolution through time (1956 to 1995) of the morphodynamic processes.

The recognition and characterization of the geologic and geomorphologic units permits to define natural environments, that correspond to “morphologic domains”, where specific morphodynamic processes are developed e.g., karstic landforms are characterized for solution, soft and clastic sediments that morphologically correspond to low to intermediate hills are more susceptible to erosive processes like sheet, rill and gully erosion.

The study of the aspects described above, becomes a preliminary step to identify the associations and relationships between natural components of the environment e.g., geology, geomorphology, morphodynamic processes and human activities e.g., land use and land cover changes and asphaltisation. These relationships will be studied in Chapter 5. The synthesis of the generated information will permit to determine and conclude in a later stage about the causes that contribute to the land degradation process that affects the Tabernas area.

Different classification systems have been proposed to assess the geomorphology of a particular region. The terrain mapping unit approach, followed in this chapter, facilitated the integration of geoinformation and permitted the characterization and synthesis of geomorphologic aspects (morphogenetic and morphometric) in a GIS environment to support the geomorphologic mapping. In addition, the use of remotely sensed data (Landsat and ASTER imagery and aerial photographs) complemented with information acquired directly in the field was a relevant aspect for the definition of morphologic boundaries in the geomorphologic mapping.
Chapter 5

Morphodynamic processes, Geomorphology and their Relationships with Natural Components of the Environment and Human Activities

5.1 Introduction

This chapter is dedicated to explore the relationships that permit to establish the influence of natural elements of the environment, e.g., geology and geomorphology, and human activities, e.g., changes in the land use, land cover patterns and the road construction with the development of the morphodynamic processes through the different years of data acquisition in the study area. To achieve this, GIS overlay operations were performed between the thematic maps that compose the spatial dataset constructed for the Tabernas desert. Each morphodynamic map corresponding to the years (1956, 1981 and 1995) was overlaid with the distribution of natural elements of the environment and the ones representing human activities. The data obtained in the attribute tables from this operation consist of the areal extent of the different morphodynamic processes occurring in the lithologic and geomorphologic units and those related to the land use and land cover changes and the road construction and development through time. Finally, for further analysis, this numerical data was transferred and processed in a spreadsheet (M.S. EXCEL) and tables and graphs were obtained for each particular instance of overlay operations.
5.2 Morphodynamic Processes and their Relationships with Natural Components of the Environment

This section explores the relationships between the geology and geomorphology with the geomorphologic processes identified in the study area. Overlay operations were used to establish the areal distribution of erosive and solution processes among the different lithologic and geomorphologic units.

5.2.1 Morphodynamic processes and geology

The results of overlaying the geologic map with the maps of morphodynamic processes for the years 1956, 1981 and 1995 show their evolution through time in the different lithologic units, as well as their susceptibility to certain types of processes. In this section, the analysis is focused in those units (Tables 5.1 and 5.2).

Table 5.1: Area of morphodynamic processes in 1956 affecting the geologic formations in the Tabernas area.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Lithology</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>Se</th>
<th>Re</th>
<th>Rs</th>
<th>MHSr</th>
<th>Ge</th>
<th>Gs</th>
<th>So</th>
<th>Ss</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
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Se: Sheet erosion  Rs: Rill and sheet erosion  Ge: Gully erosion  So: Solution  Re: Rill erosion  MHSr: Moderate to High Sheet and Rill Erosion  Gs: Gully and sheet erosion  Ss: Sheet erosion and Solution

The unit formed by marls, sandstones and conglomerates (Tbc11–12) presents a high susceptibility to develop erosive processes and nearly 51% of it is affected. The soft nature of the marls and sandstones and their high erodibility are the main conditions for the development of rill, sheet and gully erosion. Particularly rill and sheet erosion, are the processes more representative in terms of extent and depth of influence on this unit.

In the same geologic formation (Tbc11–12), rill and sheet erosion presents an increase from 1020 Ha in the year 1956, to 1152 Ha in 1995. It means an increase of 132 Ha. Another process that presents significant increment in extent through time in this unit is the gully and sheet erosion. From 23.48 Ha in 1956, it passed to 282.2 Ha in 1995. This fact is also related to the decrease in the areas affected by sheet and gully erosion as individual processes.
5.2. Morphodynamic Processes and their Relationships with Natural Components of the Environment

Table 5.2: Area of morphodynamic processes in 1995 affecting the geologic formations in the Tabernas area.

<table>
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<tr>
<th>Symbol/Compositional Unit</th>
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<th>Re</th>
<th>Rs</th>
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<th>Gs</th>
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<td>Conglomerates and</td>
<td>2213</td>
<td>7.97</td>
<td>343.76</td>
<td>40.56</td>
<td>7.64</td>
<td>65.32</td>
<td>0.10</td>
<td></td>
<td>0.04</td>
<td>457.48</td>
<td>20.67</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Conglomerates</td>
<td>482.04</td>
<td>1.75</td>
<td>274.08</td>
<td>53.33</td>
<td>25.38</td>
<td>33.08</td>
<td>35.92</td>
<td>5.96</td>
<td></td>
<td>321.34</td>
<td>14.27</td>
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</tr>
<tr>
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<td>2229.76</td>
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<td>112.18</td>
<td>888.52</td>
<td>701.4</td>
<td>324.12</td>
<td>6313.44</td>
<td>22.73</td>
<td></td>
</tr>
</tbody>
</table>

Se: Sheet erosion
Re: Rill erosion
Rs: Rill and sheet erosion
Ge: Gully erosion
Gs: Gully and sheet erosion
So: Solution
Ss: Sheet erosion and Solution

Another unit with high susceptibility to different morphodynamic processes is the graphitic schists and quartzite (PC–Pn) of the Nevado Filabride Complex. It was observed during the fieldwork the high structural control that present this unit due to the fact that it is strongly foliated. The foliation planes represent discontinuities and the sandy to coarse nature of the scarce soils that are developed from these materials favor the action of the erosive agents. Processes such as rill erosion present an increase of 78.36 Ha from 1956 to 1995. Gully and sheet erosion also present a high increase in the unit named marls, sandstones and conglomerates. From 162.92 Ha affected in 1956, it passed to 409.12 Ha in 1995, which represents a high increase in the erosion processes.

Solution processes in coexistence with sheet erosion and affect only particular geologic units. The former is more concentrated in the limestones (Tbc11–12), even though, in some small bodies of the same type of rock located in the foothills of the Sierra de Los Filabres, the development of sheet erosion besides the solution process was identified. The second one is more representative of the gypsum bodies (Tbcv–12). Due to the particular climatic conditions of the study area, these processes do not present a high dynamism through time. In particular, the areas affected by sheet erosion and solution show an increase from 282 Ha in 1956 to 324.12 Ha in 1995.

5.2.2 Morphodynamic processes and geomorphology

In the area of Tabernas, the geology exerts a strong control in the landforms produced by the landscape evolution through time. This is the main reason why the results of overlaying the geomorphologic map with the maps of morphodynamic processes for the years 1956, 1981 and 1995 present high similarity with the results presented in the previous section.

The geomorphologic unit named “Badlands” has a high susceptibility to a great variety of erosive processes. The parent material of this unit is composed by marls, sandstones and conglomerates (Tbc11–12). In the previous section, its high susceptibility to specific type of processes such as rill and sheet erosion, and gully and sheet erosion was demonstrated. It will be interesting in this section to consider the ove-
5.2. Morphodynamic Processes and their Relationships with Natural Components of the Environment

Table 5.3: Area of morphodynamic processes in 1956 affecting the geomorphologic units in the Tabernas area.

<table>
<thead>
<tr>
<th>Geomorphologic Units</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>Se</th>
<th>Rs</th>
<th>MHSr</th>
<th>Ge</th>
<th>Gs</th>
<th>So</th>
<th>Ss</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate Relief of Sierra de los Filabres</td>
<td>2491</td>
<td>9.39</td>
<td>593</td>
<td>137</td>
<td>143</td>
<td>74</td>
<td>112</td>
<td>69</td>
<td>719</td>
<td>26.94</td>
<td></td>
</tr>
<tr>
<td>Moderate Relief of Sierra Alhamilla</td>
<td>967.92</td>
<td>3.65</td>
<td>28.16</td>
<td>30.72</td>
<td>2.76</td>
<td>151.84</td>
<td>15.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steep Relief of Sierra Alhamilla</td>
<td>3198.52</td>
<td>12.06</td>
<td>176.16</td>
<td>3.12</td>
<td>2.8</td>
<td>182.08</td>
<td>5.69</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>East-West Elongated Low Ridges</td>
<td>1678.46</td>
<td>6.33</td>
<td>458.12</td>
<td>8.72</td>
<td>8.72</td>
<td>8.72</td>
<td>486.84</td>
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<td>4.49</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>719.84</td>
<td>28.94</td>
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<tr>
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<td>1.07</td>
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<td>95.84</td>
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</tr>
<tr>
<td>Bad lands</td>
<td>1388.76</td>
<td>5.24</td>
<td>59.36</td>
<td>43</td>
<td>376.68</td>
<td>149.48</td>
<td>82.48</td>
<td>10.48</td>
<td>721.6</td>
<td>27.96</td>
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<tr>
<td>Low Hills</td>
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<td>652.08</td>
<td>10.36</td>
<td>497.84</td>
<td>91.76</td>
<td>21.32</td>
<td>1128.04</td>
<td>25.18</td>
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</tr>
<tr>
<td>Peneplanation Surfaces</td>
<td>848.36</td>
<td>3.2</td>
<td>91.48</td>
<td>2.84</td>
<td>121.24</td>
<td>28.4</td>
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<td>0.68</td>
<td>264.28</td>
<td>31.15</td>
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<td>13.52</td>
<td>32.2</td>
<td>16.8</td>
<td>735.24</td>
<td>28.6</td>
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</tr>
<tr>
<td>Alluvio-Colluvial Deposits</td>
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<td>264.08</td>
<td>15.8</td>
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<td></td>
<td></td>
</tr>
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<td>Alluvial Terraces</td>
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<td>4.08</td>
<td>0.08</td>
<td>21.36</td>
<td>6.6</td>
<td>35.28</td>
<td>9.32</td>
<td>74.72</td>
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<td>17.12</td>
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<tr>
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<td>1333.28</td>
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<td>745.24</td>
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</table>

Se: Sheet erosion Rs: Rill and sheet erosion Ge: Gully erosion So: Solution
MHSr: Moderate to High Sheet and Rill Erosion Gs: Gully and sheet erosion Ss: Sheet erosion and Solution

Table 5.4: Area of morphodynamic processes in 1981 affecting the geomorphologic units in the Tabernas area.

<table>
<thead>
<tr>
<th>Geomorphologic Units</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>Se</th>
<th>Rs</th>
<th>MHSr</th>
<th>Ge</th>
<th>Gs</th>
<th>So</th>
<th>Ss</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate Relief of Sierra de los Filabres</td>
<td>2491</td>
<td>9.39</td>
<td>482.92</td>
<td>47.04</td>
<td>215.08</td>
<td>215.96</td>
<td>180.52</td>
<td>6.04</td>
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<tr>
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<td>66.88</td>
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<td>3.56</td>
<td>178</td>
<td>18.39</td>
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<td></td>
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<tr>
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<td>3198.52</td>
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<td>282.36</td>
<td>4.24</td>
<td>4.52</td>
<td>291.12</td>
<td>9.10</td>
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</tr>
<tr>
<td>East-West Elongated Low Ridges</td>
<td>1678.46</td>
<td>6.33</td>
<td>403.96</td>
<td>39.68</td>
<td>8.76</td>
<td>452.4</td>
<td>27.00</td>
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<tr>
<td>Limestone Hills</td>
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<td>4.49</td>
<td>6.4</td>
<td>47.32</td>
<td>600.4</td>
<td>654.12</td>
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<td>91.76</td>
<td>21.32</td>
<td>1128.04</td>
<td>25.18</td>
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<tr>
<td>Peneplanation Surfaces</td>
<td>848.36</td>
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<td>69.96</td>
<td>4.08</td>
<td>112.92</td>
<td>30.12</td>
<td>21.88</td>
<td>0.56</td>
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<td>18.8</td>
<td>13.52</td>
<td>32.2</td>
<td>16.8</td>
<td>735.24</td>
<td>28.6</td>
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<td>0.08</td>
<td>21.36</td>
<td>6.6</td>
<td>35.28</td>
<td>9.32</td>
<td>74.72</td>
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<tr>
<td>Alluvial Plains</td>
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<td>48.08</td>
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<td>23.24</td>
<td>107.52</td>
<td>9.38</td>
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<tr>
<td>Total Area</td>
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<td>175.44</td>
<td>1333.28</td>
<td>307.32</td>
<td>362.72</td>
<td>26.2</td>
<td>738.8</td>
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</tr>
</tbody>
</table>

Se: Sheet erosion Rs: Rill and sheet erosion Ge: Gully erosion So: Solution
MHSr: Moderate to High Sheet and Rill Erosion Gs: Gully and sheet erosion Ss: Sheet erosion and Solution

rall results by aggregating the total area affected by morphodynamic processes in this particular unit. From Tables 5.3, 5.4 and 5.5, it can be observed an increment from 51.96% of the area of this unit affected in 1956 to 66.63% of the area affected in 1995. This value represents an increase of 14.67% of the area affected in this period of time.

The geomorphologic unit “Moderate Relief of the Sierra de Los Filabres” is to a great extent composed of graphitic schists, quartzites and micaceous gneisses from the Nevado Filabride Complex. The overall area affected by the different morphodynamic processes increased from 28.94% in 1956 to 46.14% in 1981 and finally it reached 47.80% in 1995. This represents an increment of 18.86% in 50 years. The major increment occurred during the first 25 years of recorded data, and it covered 17.2% of the total area of the unit.

The geomorphologic units that form the Sierra Alhamilla also present an increase in the area affected by morphodynamic processes. The unit “Steep Relief of Sierra
5.3 Morphodynamic Processes and their relationships with human activities

The area of Tabernas has been exposed to different kinds of pressures on its natural environment by human activities since historic times, e.g., agricultural activities, mining and quarrying, groundwater extraction, overgrazing and deforestation. Some of them have been accentuated in the recent decades. The availability of multi-temporal aerial photographs has permitted to evaluate three parameters identified as pressures on the environment during the last 50 years. Different changes in the land use, land cover patterns and the road construction and development have been detected using aerial photographs from the years 1956, 1981 and 1995 [2].

The quantification of the changes in natural elements (land cover) and man made elements (land use and road construction and development) has permitted to establish a baseline to assess their influence in the land degradation. Previous changes in the past that could have been greater than the ones already identified have not been detected due to the lack of records of historical data. The scale of previous and this survey, pose a certain limitation to evaluate the contribution of the extent of the changes to the development of the morphodynamic processes. The geomorphic domains in which particular processes are developed are scale dependent and consequently affect the relationships that can be established between natural environmental components and human activities.

The available information produced in previous studies e.g., [2], ELANEM reports ([54], http://www.citimac.unican.es/ELANEM/portada.html) will be combined...
5.3. Morphodynamic Processes and their relationships with human activities

Table 5.6: Areas with land use changes from 1956 to 1981 that have been affected by morphodynamic processes.

<table>
<thead>
<tr>
<th>Processes 1981</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>DF</th>
<th>IRTO</th>
<th>Pr/Hu/Os</th>
<th>NITO/A</th>
<th>MU</th>
<th>NITO</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>2635.08</td>
<td>42.28</td>
<td>197.32</td>
<td>8.6</td>
<td>82.56</td>
<td>7.92</td>
<td>0.08</td>
<td>2.52</td>
<td>299</td>
<td>11.35</td>
</tr>
<tr>
<td>Re</td>
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</tr>
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<tr>
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<tr>
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<td>29.84</td>
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<tr>
<td>So</td>
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<td>45.92</td>
<td>6.22</td>
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<td>197.32</td>
<td>8.6</td>
<td>82.56</td>
<td>7.92</td>
<td>0.08</td>
<td>2.52</td>
<td>448.36</td>
<td>7.19</td>
</tr>
</tbody>
</table>

Se: Sheet erosion  Rs: Rill and sheet erosion  DF: Dry Farming
Re: Rill erosion   MHSr: Moderate to High Sheet and Rill Erosion  IRTO: Irrigated Tree, Olive
Ge: Gully erosion  So: Solution  Pr/Hu/Os: Protected and Hunting/Open space
Gs: Gully and sheet erosion  Ss: Sheet erosion and Solution  NITO/A: Non-Irrigated Tree Olive/Almond
MU: Mixed Use  NITO: Non Irrigated Trees, Others

with the one generated in the present study, regarding the interpretation of the morphodynamic processes to establish relationships that permit to clarify the causes that generate or influence the development of geomorphologic processes as an indicator of the ongoing land degradation in this particular study area.

5.3.1 Morphodynamic processes and changes in land use

**Morphodynamic processes in 1981 and changes in land use between 1956 and 1981**

As a result of the overlaying operation between the map of morphodynamic processes in 1981 with the changes detected in land use pattern between 1956 and 1981 [2], it can be established that from a total of 6232.36 Ha affected in 1981, 448.36 Ha coincide with areas where changes in the land use have been mapped. These areas correspond to only 7.19% (Table 5.6).

Sheet erosion is the morphodynamic process that presents the greater extension where different types of land use changes have been identified with a total of 299 Ha. From that value, 197.32 Ha correspond to “Dry Farming” (the land use class that presents the greatest changes for this particular period of time, with a reduction of area of nearly 18%, [2]). This particular land use, contributes in 66% to the areas affected by the different morphodynamic processes and 44% corresponds to areas of sheet erosion (Figure 5.1).

From Figure 5.2, the areas enclosed by rectangular forms represent places that have undergone changes in the land use pattern that coincide with areas affected by morphodynamic processes. Those changes may have accelerated the development of the erosive processes, such as sheet, rill and gully erosion. In the south-east part of the Sierra Alhamilla (bottom of Figure 5.2), areas that have lost their original vegetal cover, have developed sheet erosion that did not exist in the year 1956. In the central-western part of Figure 5.2, an elongated north-south area of 29.84 Ha affec-
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.1: Areas with land use changes from 1956 to 1981 that have been affected by morphodynamic processes.

Table 5.7: Areas with land use changes from 1981 to 1995 that have been affected by morphodynamic processes.

<table>
<thead>
<tr>
<th>Processes 1995</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>DF</th>
<th>Pr/Hu/Os</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
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<td>79.92</td>
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<td>0.00</td>
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<td></td>
</tr>
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<td>0.68</td>
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<td>14.08</td>
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<td>1.68</td>
<td>0.16</td>
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</tr>
<tr>
<td>So</td>
<td>703.56</td>
<td>11.12</td>
<td>16.72</td>
<td>0.16</td>
<td>16.88</td>
<td>2.40</td>
</tr>
<tr>
<td>Sa</td>
<td>324.12</td>
<td>5.13</td>
<td>2.88</td>
<td>5.92</td>
<td>8.8</td>
<td>2.72</td>
</tr>
<tr>
<td>Sa</td>
<td>77.92</td>
<td>1.23</td>
<td>0</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Area</strong></td>
<td><strong>6246.28</strong></td>
<td><strong>99.99</strong></td>
<td>104.76</td>
<td>10.8</td>
<td>115.56</td>
<td>1.85</td>
</tr>
</tbody>
</table>

Se: Sheet erosion  
Re: Rill erosion  
Rs: Rill and sheet erosion  
Ge: Gully erosion  
Gs: Gully and sheet erosion  
So: Solution  
Sa: Sheet erosion and Solution  
DF: Dry Farming  
Pr/Hu/Os: Protected and Hunting/Open space

The changes in the land use pattern were detected only for the classes “Dry Farming”.

**Morphodynamic processes in 1995 and changes in land use from 1981 to 1995**

Major changes in the land use pattern in the area of Tabernas have occurred in the period 1956–1981. This is the reason why, as a result of overlaying the map of morphodynamic processes in 1995 with the map of the changes detected in land use pattern from 1981 to 1995, it can be established that from a total of 6246.28 Ha affected by morphodynamic processes in 1995, 115.56 Ha, coincide with areas where changes in the land use pattern have been detected. It only corresponds to 1.85% (Table 5.7).
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.2: Areas of land use changes between 1956 and 1981. The squares represent areas that coincide with morphodynamic processes. Source of land use change map (2)

ming” and “Protected-Hunting-Open Space” (Figure 5.3). Again, areas that have undergone a reduction in the Dry Farming class represent the high contribution to areas affected by morphodynamic processes with 104.76 Ha. That means a 90.65% of the total area of the land use changes in this period of time. Areas affected by sheet erosion with changes in “Dry Farming” sum 79.92 Ha; which corresponds to 69.15% of the gross changes.

Even though the small percentage of areas affected by changes in the land cover pattern, Figure 5.4 presents those areas enclosed by rectangular forms that coincide with the presence of morphodynamic processes.

From the values calculated and the visualization of the areas that have undergone changes in the land use pattern in the periods of time considered, it can be noticed that for some particular areas, such as the Sierra Alhamilla and the central-western part those changes are contemporaneous and could be related with the development of sheet erosion and gully erosion, respectively. Even though the area affected by morphodynamic processes that have undergone changes in land use represent a few percentages of the study area, the changes have exerted a visible influence to the development of the processes. The nature of the parent material and the morphology of the terrain have played a major role in the development of the different morphodynamic processes.
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.3: Areas with land use changes from 1981 to 1995 that have been affected by morphodynamic processes.

Table 5.8: Areas with land cover changes from 1956 to 1981 that have been affected by morphodynamic processes.

<table>
<thead>
<tr>
<th>Processes 1981</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>SC</th>
<th>SBCT</th>
<th>SBGC</th>
<th>DBGC</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>2635.08</td>
<td>42.28</td>
<td>123.24</td>
<td>2.32</td>
<td>77.04</td>
<td>5.8</td>
<td>208.4</td>
<td>7.91</td>
</tr>
<tr>
<td>Re</td>
<td>175.44</td>
<td>2.81</td>
<td>2.4</td>
<td>2.4</td>
<td>1.37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs</td>
<td>1421.72</td>
<td>22.81</td>
<td>13.48</td>
<td>13.48</td>
<td>0.95</td>
<td></td>
<td>13.48</td>
<td>0.95</td>
</tr>
<tr>
<td>MHSr</td>
<td>481.52</td>
<td>7.73</td>
<td>1.64</td>
<td>1.64</td>
<td>0.34</td>
<td></td>
<td>1.64</td>
<td>0.34</td>
</tr>
<tr>
<td>Gs</td>
<td>54.08</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>439.32</td>
<td>7.05</td>
<td>24.64</td>
<td>24.64</td>
<td>5.61</td>
<td></td>
<td>24.64</td>
<td>5.61</td>
</tr>
<tr>
<td>So</td>
<td>738.8</td>
<td>11.85</td>
<td>29.2</td>
<td>29.2</td>
<td>3.95</td>
<td></td>
<td>29.2</td>
<td>3.95</td>
</tr>
<tr>
<td>Ss</td>
<td>286.4</td>
<td>4.6</td>
<td>3.36</td>
<td>44.4</td>
<td>47.76</td>
<td>16.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>6232.36</td>
<td>100</td>
<td>197.96</td>
<td>2.32</td>
<td>121.44</td>
<td>5.8</td>
<td>327.52</td>
<td>5.26</td>
</tr>
</tbody>
</table>


5.3.2 Morphodynamic processes and changes in land cover

Morphodynamic processes in 1981 and changes in land cover between 1956 and 1981

As a result of the overlaying operation between the map of morphodynamic processes in 1981 with the changes detected in land cover between 1956 and 1981, it can be establish that from a total of 6232.36 Ha affected by morphodynamic processes in 1981, 327.52 Ha, coincide with areas where changes in the land cover pattern have been detected. This area corresponds to 5.26% (Table 5.8).

Sheet erosion is the morphodynamic process that presents greater extent where different types of land cover changes have been identified with 208.4 Ha, 63.62% of the total area. The class “Seasonal Cultivation”, which presents a similar spatial distribution with the land use class “Dry Farming”, was the land cover category that presented the greatest changes for this particular period of time, with a reduction of
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.4: Areas with land use changes between 1981 and 1995. The rectangular forms represent areas that overlay with morphodynamic processes. Source of the land use change map [2]

area of nearly 16%, [2]. By adding the areas that have undergone changes in “Seasonal Cultivation”, the contribution to the areas affected by the different morphodynamic processes is 197.96 Ha. This represents 60.44%, and from this percentage, a 44% correspond to areas of sheet erosion (Figure 5.5).

Another land cover category that represents a high contribution to the total area affected by morphodynamic processes is the “Sparse Bush and Grass Cover”. As a matter of fact, this land cover class can be associated as an indication of erosive morphology. A total of 121.44 Ha, which represent the 37%, coincide with areas affected by morphodynamic processes, and sheet erosion represents 63.43% of this area. The other percentage corresponds to areas affected by sheet erosion combined with solution processes. The changes in the land cover pattern do not have a strong influence in the acceleration of solution processes. The later in the Tabernas area are much slower than the erosive ones (Table 5.8 and Figure 5.5)

From Figure 5.6, it can be seen that the areas enclosed by rectangular forms represent those that have undergone changes in the land cover pattern. Furthermore, some of them also overlay with terrain that has been contemporaneously affected by morphodynamic processes that were not present in 1956. As in the case of the land use changes, they could represent a factor that has accelerated the development of different morphodynamic processes. In the Sierra Alhamilla, areas that have lost their original vegetation present sheet erosion that did not exist in the year 1956. In the central-western part an elongated north-south area of 24.64 Ha affected by gully erosion, coincides with an area of changes in the seasonal cultivation.
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.5: Areas with land cover changes from 1956 to 1981 that have been affected by morphodynamic processes.

Morphodynamic processes in 1995 and changes in land cover between 1981 and 1995

As a result of the overlaying operation between the map of morphodynamic processes in 1995 with the changes detected in land cover between 1981 and 1995, it can be established that from a total of 6246.28 Ha affected by morphodynamic processes in 1995, 123.44 Ha coincide with areas where changes in the land cover pattern have been detected. It corresponds to only 1.98% (Table 5.9).

In this particular period of time (1981–1995), the changes in the land cover pattern were detected only for the classes “Seasonal Cultivation” and “Sparse Bush and Grass Cover”. Again the areas that present a reduction in the “Seasonal Cultivation” class, represent the high contribution to areas affected by morphodynamic processes with 114.04 Ha, that means the 92.38%. Areas affected by sheet erosion with changes in “Seasonal Cultivation” sum up to 89.2 Ha; which correspond to 78.2%. The areas that have undergone changes in “Sparse Bush and Grass Cover” and are affected by morphodynamic processes sum up to 10.8 Ha and only represent the 8.74% (Table 5.9 and Figure 5.7).

From Figure 5.8, it can be seen that the areas enclosed by rectangular forms have undergone changes in the land cover pattern that may have accelerated the development of different morphodynamic processes. In the Sierra Alhamilla, a decrease in the seasonal cultivation coincides with the development of sheet erosion.

The results obtained by the evaluation of the influence of the land use and land cover changes in the distribution of morphodynamic processes show that small portions of the study area that have undergone changes introduced by human activities are affected by morphodynamic processes. This is specially so far sheet erosion and to lesser extent, gully erosion. From this, it can be concluded that the dynamic of the geomorphologic processes depends more from the natural conditions existent in the area than from changes introduced by humans. Even though, this changes can exert a certain influence and can be a factor that accelerates, or in fragile areas, can introduce some modifications that overcome thresholds to start the development of
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.6: Areas of land cover changes between 1956 and 1981. The rectangular forms represent areas that overlay with morphodynamic processes. Source of the land use change map (2).

Table 5.9: Areas with land cover changes from 1981 to 1995 that have been affected by morphodynamic processes.

<table>
<thead>
<tr>
<th>Processes</th>
<th>1995 Area (Ha)</th>
<th>Area (%)</th>
<th>SC</th>
<th>SBGC Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>2235.24</td>
<td>35.34</td>
<td>89.2</td>
<td>4.72</td>
<td>93.92</td>
</tr>
<tr>
<td>Re</td>
<td>234.04</td>
<td>3.7</td>
<td></td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Rs</td>
<td>1746.48</td>
<td>27.62</td>
<td>0.68</td>
<td>0.68</td>
<td>0.00</td>
</tr>
<tr>
<td>Ge</td>
<td>112.16</td>
<td>1.77</td>
<td>3.16</td>
<td>3.16</td>
<td>178.53</td>
</tr>
<tr>
<td>Gs</td>
<td>890.68</td>
<td>14.08</td>
<td>1.4</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>So</td>
<td>703.56</td>
<td>11.12</td>
<td>16.72</td>
<td>0.16</td>
<td>16.88</td>
</tr>
<tr>
<td>Ss</td>
<td>324.12</td>
<td>5.13</td>
<td>2.88</td>
<td>5.92</td>
<td>8.8</td>
</tr>
<tr>
<td>Sa</td>
<td>77.92</td>
<td>1.23</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Area</td>
<td>6246.28</td>
<td>99.99</td>
<td>114.04</td>
<td>10.8</td>
<td>123.44</td>
</tr>
</tbody>
</table>

Se: Sheet erosion  Rs: Rill and sheet erosion  SC: Seasonal Cultivation
Re: Rill erosion  MHSr: Moderate to High Sheet and Rill Erosion  SBGC: Sparse Bush and Grass Cover
Ge: Gully erosion  So: Solution  and Gras Cover
Gs: Gully and sheet erosion  Ss: Sheet erosion and Solution
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.7: Areas with land cover changes from 1981 to 1995 that have been affected by morphodynamic processes.

5.3.3 Morphodynamic processes and asphaltisation

In the Tabernas area, the distribution of the asphaltisation process from the 50s to the year 2000 was presented in Section 2.8.4. These results will be integrated with the morphodynamic process mapping, to establish relationships that permit to identify whether there are influences between road construction and the development of morphodynamic processes, particularly those related with erosion.

**Morphodynamic processes and asphaltisation in the 50s**

The situation of the distribution of morphodynamic processes in 1956 and the different road types in 1950, was obtained by overlaying both maps. It is presented in Figure 5.9. This year will be considered as a baseline to determine and relate evolution of morphodynamic processes related to road construction.

From Table 5.10 and Figure 5.10 it can be observed that nearly the 17% of the two classes of roads existent at this time were affected by morphodynamic processes. The class “Asphalted Road” (7-9 m width)”, is affected in 11.76 Ha by the different processes. Among them, sheet erosion with 14.68 Ha constitutes the most important one with a contribution of 87% to the total affected area. The rest is a contribution of processes like, rill, rill and sheet erosion and solution. The gravel roads are only affected by sheet erosion and from 42.12 Ha of roads, 7.12 are affected by this process. That means the 16.9%.

**Morphodynamic processes and asphaltisation in the 80s**

The situation of the distribution of morphodynamic processes in 1981 and the different road types in 1985 is presented in Figure 5.11, which is the result of the overlaying operation between both maps.
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.8: Areas of land cover changes between 1956 and 1981. The rectangular forms represent areas that overlay with morphodynamic processes. Source of land cover change map [2]

From Tables 5.10 and 5.11 it can be observed an increase from 18.88 Ha affected in the 50s to 22.24 Ha affected in the 80s. A total of 21.91 Km of new roads was constructed in this period of time. From a total area of constructed roads of 152.2 Ha, the areas affected by geomorphologic processes (22.24 Ha) correspond to 14.61%.

Table 5.11 shows that nearly half of the area affected by morphodynamic processes is a direct contribution of sheet erosion. This type of process is more concentrated in the classes “Asphalted Roads (3 m width)” and “Gravel Roads”, with 4.08 and 5.6 Ha, respectively. The gravel roads are the ones that present the greater extent of affected areas, with nearly 10 Ha that represent 18.19%. The second class is the “Asphalted Roads (7 m width)” with 16% of area affected.

Rill and sheet erosion, represents the second morphodynamic process that con-

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Area (Ha)</th>
<th>Se</th>
<th>Re</th>
<th>Rs</th>
<th>So</th>
<th>Ss</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asph. Rd</td>
<td>70.4</td>
<td>7.56</td>
<td>1.2</td>
<td>0.12</td>
<td>0.32</td>
<td>2.56</td>
<td>11.76</td>
<td>16.70</td>
</tr>
<tr>
<td>Grav. Rd</td>
<td>42.12</td>
<td>7.12</td>
<td>0.12</td>
<td>0.32</td>
<td>2.56</td>
<td>7.12</td>
<td>16.90</td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>112.52</td>
<td>14.68</td>
<td>1.2</td>
<td>0.12</td>
<td>0.32</td>
<td>2.56</td>
<td>18.88</td>
<td>16.78</td>
</tr>
</tbody>
</table>

Asph. Rd: Asphalted Road
Grav. Rd: Gravel Road
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.9: Road distribution in 1950 overlaid with morphodynamic processes in 1956. The enclosed areas with rectangular forms represent affected areas of the different road classes. Source of road map (2)

Figure 5.10: Areas of the different road classes affected by morphodynamic processes in the 50s.
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.11: Road distribution in 1985 overlaid with morphodynamic processes in 1981. The enclosed areas with rectangular forms represent affected areas of the different road classes. Source of road map (2)

Table 5.11: Areas of the different road classes affected by morphodynamic processes in the 80s.

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Area (Ha)</th>
<th>Se</th>
<th>Re</th>
<th>Rs</th>
<th>Ge</th>
<th>Ss</th>
<th>So</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asp. Rd. 7m</td>
<td>40.76</td>
<td>1.84</td>
<td>0.36</td>
<td>1.04</td>
<td>0.88</td>
<td>2.4</td>
<td>6.52</td>
<td>16.00</td>
<td></td>
</tr>
<tr>
<td>Asp. Rd. 6m</td>
<td>12</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.00</td>
<td></td>
</tr>
<tr>
<td>Asp. Rd. 5m</td>
<td>12.76</td>
<td>0.36</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.96</td>
<td></td>
</tr>
<tr>
<td>Asp. Rd. 4m</td>
<td>31.48</td>
<td>4.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.96</td>
<td></td>
</tr>
<tr>
<td>Grav Rd.</td>
<td>55.2</td>
<td>5.6</td>
<td>0.28</td>
<td>3.36</td>
<td>0.8</td>
<td></td>
<td></td>
<td>18.19</td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>152.2</td>
<td>12.36</td>
<td>0.64</td>
<td>4.4</td>
<td>1.68</td>
<td>2.76</td>
<td>0.4</td>
<td>22.24</td>
<td>14.61</td>
</tr>
</tbody>
</table>

Asp. Rd. X: Asphalted Road X m width
Grav. Rd: Gravel Road
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.12: Areas of the different road classes affected by morphodynamic processes in the 80s.

tributes to the total area affected with, 4.4 Ha. They are distributed among the road classes, “Asphalted Roads (7 m width)”, with 1.04 Ha; and “Gravel Roads” with 3.36 Ha (Figure 5.12).

From Figure 5.11 it can be observed in the southwestern corner that a new area classified as affected by gully erosion that was not in the morphodynamic map of 1956, coincides with the new road constructed as an access to the television tower located in the Sierra Alhamilla Figure Foto???? presents a closest view of this particular area.

Also, in the southwestern part of the study area, along the CN-340 there were small areas affected by rill erosion in the 50s (Figure 5.9). In the 80s, these areas are affected by gully erosion (Figure 5.11), which can indicate a probable evolution from one type of process to the other. This can be a consequence of the road development and a non-technical management of the runoff water after the road construction and maintenance.

**Morphodynamic processes in 1995 and asphaltisation in 2000**

The situation of the distribution of morphodynamic processes in 1995 and the different road types in the year 2000, was obtained by overlaying both maps Figure 5.13. It has certain similarity with the situation in the 80s. It was assumed that five years of difference between the two maps is not relevant to analyze this aspect, considering the dynamism of the geomorphologic processes, presented in Section 4.

From Tables 5.11 and 5.12 it can be observed an increase from 22.24 Ha affected in the 80s to 32.84 Ha affected in the year 2000. A total of 32.45 Km is the length of constructed roads, which means an increment compared with the situation in the 80s of 10.54 Km of new roads.

Again the areas of constructed roads affected by sheet erosion are the ones that highly contribute to the total areas affected by morphodynamic processes. From 12.36 Ha in the 80s, an increment of 8.36 Ha was obtained for the year 2000. In this period, the road class that presents the highest contribution to the areas affected by sheet erosion is the “Asphalted Road (5 m width)”, with 8.04 Ha; followed by
5.3. Morphodynamic Processes and their relationships with human activities

Figure 5.13: Road distribution in 2000 overlaid with morphodynamic processes in 1995. The enclosed areas represent the overlap between the road classes and the processes.
Source of road map (2)

Table 5.12: Areas of constructed roads in 2000, affected by morphodynamic processes.

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Area (Ha)</th>
<th>Se</th>
<th>Re</th>
<th>Rs</th>
<th>Ge</th>
<th>Gs</th>
<th>Ss</th>
<th>So</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asp. Rd. 9-7m</td>
<td>85.71</td>
<td>7</td>
<td>0.16</td>
<td>0.88</td>
<td>0.92</td>
<td>2.64</td>
<td>0.24</td>
<td>11.84</td>
<td>13.81</td>
<td></td>
</tr>
<tr>
<td>Asp. Rd. 5m</td>
<td>49.24</td>
<td>8.04</td>
<td>0.6</td>
<td>0.24</td>
<td>8.88</td>
<td>18.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asp. Rd. 3m</td>
<td>21.52</td>
<td>0.8</td>
<td>3.96</td>
<td>4.76</td>
<td>22.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grav. Rd.</td>
<td>38</td>
<td>4.88</td>
<td>0.52</td>
<td>0.36</td>
<td>0.24</td>
<td>1.36</td>
<td>7.36</td>
<td>19.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area (Ha)</td>
<td>194.47</td>
<td>20.72</td>
<td>0.76</td>
<td>5.36</td>
<td>1.52</td>
<td>0.24</td>
<td>4</td>
<td>32.84</td>
<td>16.89</td>
<td></td>
</tr>
</tbody>
</table>

Asp. Rd: Asphalted Road X m width
Grav. Rd: Gravel Road
5.4 Geomorphology and its relationships with human activities

Figure 5.14: Areas of constructed roads in 2000, affected by morphodynamic processes.

the class “Asphalted Road (7-9 m width)” with 7 Ha Figure 5.14.

As in the 80s, the areas affected by rill and sheet erosion, are the second contributors to the total areas affected by morphodynamic processes. An increase from 4.4 Ha in the 80s to 5.36 Ha in the year 2000 can be observed form Tables 5.11 and 5.12. In the last year, the class “Asphalted Road (3 m width)” presents the highest extent of affectation with 3.96 Ha. The class “Asphalted road (7-9 m width)” presents 0.88 Ha affected and the “Gravel Roads” a total of 0.52 Ha.

5.4 Geomorphology and its relationships with human activities

Agricultural activities in the area of Tabernas take place in low areas. In order to develop these type of activities, the preparation of the terrain is essential. This phase deals basically with the levelling of portions of land, in order to have areas suitable to grow the crops. This type of activity, in some cases, can introduce morphological changes. Initially, in this study it was contemplated to assess the changes in the morphology of the areas where agricultural activities were practised. The scale of work and the resolution of the available data (topographic maps, ortho-photo mosaics, DEM) do not permit an assessment of those changes, due to the fact that they take place in areas of gentle slopes and morphology. Topographic data with multi-temporal coverage and higher spatial resolution is needed to assess and evaluate the geomorphologic changes that can be introduced by agricultural activities.

In the next section, the relationships between the geomorphology of the Tabernas area and the human activities will be established. Particularly those associated with the changes introduced in the land use and land cover pattern. To accomplish this, a similar procedure to the one followed in Section 5.2 was chosen. Only the overall changes in the land use and the land cover pattern between 1956 and 1995 were considered for the analysis and not the partial changes between 1956 and 1981 and between 1981 and 1995. This criterion obeyed to the fact that the spatial distribution of the geomorphologic units was considered a less dynamic factor (without changes)
Table 5.13: Areas of geomorphologic units where land use changes have taken place between 1956 and 1995.

<table>
<thead>
<tr>
<th>Geomorphologic Units</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>DF</th>
<th>DFTP</th>
<th>Pr/Hu/Os</th>
<th>MU</th>
<th>IRTO</th>
<th>NITOA</th>
<th>NITO</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate Relief of Sierra de los Filabres</td>
<td>2497</td>
<td>9.39</td>
<td>63.28</td>
<td>63.28</td>
<td>2.54</td>
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<td></td>
<td></td>
<td>63.28</td>
<td>2.54</td>
</tr>
<tr>
<td>Steep Relief of Sierra Alhamilla</td>
<td>3188.32</td>
<td>12.08</td>
<td>204.2</td>
<td>96.68</td>
<td>300.88</td>
<td>5.2</td>
<td>0.54</td>
<td></td>
<td></td>
<td>9.41</td>
<td></td>
</tr>
<tr>
<td>East-West Elongated Low Ridges</td>
<td>1675.48</td>
<td>6.33</td>
<td>20.88</td>
<td>1.56</td>
<td>22.44</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>Limestone Hills</td>
<td>1188.08</td>
<td>4.49</td>
<td>109.44</td>
<td>2.12</td>
<td>111.56</td>
<td>9.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum Hills</td>
<td>331.36</td>
<td>1.25</td>
<td>37.2</td>
<td>56.88</td>
<td>94.08</td>
<td>28.39</td>
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<tr>
<td>Isolated Hills</td>
<td>284.32</td>
<td>1.07</td>
<td>8.92</td>
<td>0.36</td>
<td>7.28</td>
<td>2.56</td>
<td></td>
<td></td>
<td></td>
<td>2.56</td>
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<tr>
<td>Low Hills</td>
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<td>5.24</td>
<td>814.76</td>
<td>106.84</td>
<td>999.36</td>
<td>71.96</td>
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<td></td>
</tr>
<tr>
<td>Bad lands</td>
<td>4479.52</td>
<td>16.91</td>
<td>36.48</td>
<td>6</td>
<td>42.48</td>
<td>0.95</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Peneplanation Surfaces</td>
<td>846.64</td>
<td>3.2</td>
<td>804.44</td>
<td>71.44</td>
<td>981.64</td>
<td>15.17</td>
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<tr>
<td>Alluvial Fans</td>
<td>1699.84</td>
<td>6.45</td>
<td>36.36</td>
<td>5.24</td>
<td>41.6</td>
<td>2.45</td>
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</tr>
<tr>
<td>Alluvial Plains</td>
<td>344.4</td>
<td>1.3</td>
<td>19.76</td>
<td>0.76</td>
<td>36.56</td>
<td>10.62</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>26482.68</td>
<td>99.99</td>
<td>2549.64</td>
<td>1.92</td>
<td>495</td>
<td>85.36</td>
<td>28.76</td>
<td></td>
<td></td>
<td>22.56</td>
<td>85.36</td>
</tr>
</tbody>
</table>

than the morphodynamic processes for the period between 1956 and 1995.

The data obtained from the attribute tables after performing the map-cross operations, consisted of the areal extent of the changes in land use and land cover in the different geomorphologic units through time. Then, this numerical data was transferred and processed in a spreadsheet (M.S. EXCEL) and finally a table and a graph were obtained for further interpretations.

5.4.1 Geomorphology and changes in land use between 1956 and 1995

As a result of the overlay operation between the geomorphologic map and the map of the changes detected in land use from 1956 to 1995, the following can be established. From a total of 26482.68 Ha that cover the different geomorphologic units, 3262.52 Ha, have undergone changes in the land use pattern in that particular period of time. This corresponds to 12.32% (Table 5.13).

The geomorphologic units “Low Hills”, “Alluvial fans”, “Alluvial plains” and “Steep relief of the Sierra Alhamilla” are the ones that present a high areal extent of changes in the different types of land use with 999.36, 981.64, 548.28 and 300.88 Ha, respectively. These values correspond to 71.96, 15.16, 48.98, and 9.41% of the extension of those particular geomorphologic units (Table 5.13 and Figure 5.15). The class “Dry Farming”, is the one that is widely distributed in the study area with 2549.64 Ha and it contributes to 78.14% of the land use changes presented in the geomorphologic units. Particularly, 81.52% of the changes presented in the “Low Hills”, and 81.94% of those presented in the “Alluvial Fans” correspond to “Dry farming”.

The second land use change of importance is the one defined as “Protected-Hunting-Open Space” and only represents 15.17% of the area covered by the different geomorphologic units. Then, classes with land use changes such as “Irrigated” and “Non Irrigated Trees”, “Mixed Use”, “Dry farming” and “Tree Plantation” represent only small portions of the terrain, without any significant extent.
5.4. Geomorphology and its relationships with human activities

5.4.2 Geomorphology and changes in land cover between 1956 and 1995

As a result of the overlaying operation between the geomorphologic map and the map of the changes detected in land cover from 1956 to 1995, it can be established that from a total of 26482.68 Ha that cover the different geomorphologic units, 3637.68 Ha have undergone changes in the land cover pattern in this particular period of time. This corresponds to 13.73\% (Table 5.14).

Table 5.14: Areas of geomorphologic units where land cover changes have taken place between 1956 and 1981.

<table>
<thead>
<tr>
<th>Geomorphologic Units</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
<th>SC</th>
<th>DBGC</th>
<th>SBCT</th>
<th>WFN</th>
<th>SBGC</th>
<th>NNV</th>
<th>Area (Ha)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod. Relief of Sierra de los Filabres</td>
<td>2497</td>
<td>9.39</td>
<td>63.28</td>
<td>63.28</td>
<td>2.544</td>
<td>3.28</td>
<td>0.399</td>
<td>3.28</td>
<td>3637.68</td>
<td>13.736</td>
</tr>
<tr>
<td>Mod. Relief of Sierra Alhamilla</td>
<td>967.92</td>
<td>3.65</td>
<td>3.28</td>
<td>3.28</td>
<td>0.339</td>
<td>0.28</td>
<td>0.339</td>
<td>0.339</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steep Relief of Sierra Alhamilla</td>
<td>3186.32</td>
<td>12.08</td>
<td>19.72</td>
<td>96.68</td>
<td>316.24</td>
<td>182.6</td>
<td>25.32</td>
<td>1.511</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East-West Elongated Low Ridges</td>
<td>1675.48</td>
<td>6.33</td>
<td>39.77</td>
<td>4.94</td>
<td>1.56</td>
<td>25.32</td>
<td>1.511</td>
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</tr>
<tr>
<td>Gypsum Hills</td>
<td>1388.76</td>
<td>5.24</td>
<td>36.48</td>
<td>36.48</td>
<td>6.02</td>
<td>2.434</td>
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<td></td>
</tr>
<tr>
<td>Badlands</td>
<td>1388.76</td>
<td>5.24</td>
<td>36.48</td>
<td>36.48</td>
<td>6.02</td>
<td>2.434</td>
<td>2.434</td>
<td>2.434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Hills</td>
<td>4479.52</td>
<td>16.91</td>
<td>832.44</td>
<td>9.52</td>
<td>110.76</td>
<td>952.72</td>
<td>21.268</td>
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<tr>
<td>Peneplanation Surfaces</td>
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<td>3.21</td>
<td>5.52</td>
<td>5.52</td>
<td>0.651</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Alluvial Fans</td>
<td>6468.84</td>
<td>24.43</td>
<td>801.88</td>
<td>12.89</td>
<td>74.92</td>
<td>22.8</td>
<td>13.892</td>
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</tr>
<tr>
<td>Alluvial-Colluvial Deposits</td>
<td>1659.84</td>
<td>6.42</td>
<td>93.33</td>
<td>5.44</td>
<td>3.44</td>
<td>47.88</td>
<td>2.817</td>
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<td></td>
</tr>
<tr>
<td>Alluvial Plains</td>
<td>344.4</td>
<td>1.3</td>
<td>16.76</td>
<td>8.96</td>
<td>0.76</td>
<td>28.48</td>
<td>8.269</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>26482.68</td>
<td>99.99</td>
<td>2575.92</td>
<td>96.68</td>
<td>335.24</td>
<td>182.6</td>
<td>418.48</td>
<td>28.76</td>
<td>3637.68</td>
<td>13.736</td>
</tr>
</tbody>
</table>

Similar results obtained in Section 5.4.1, were obtained for the distribution of changes in land cover in the different geomorphologic units. The units “Low Hills”, “Alluvial Fans”, “Alluvial Plains” and “Steep Relief of the Sierra Alhamilla”, are the most important units; where changes in the different types of land cover have occurred with 952.72, 898.8, 556.96, 799.72 Ha, respectively. These values correspond to 21.27, 13.89, 49.75 and 25\% of the extension of those particular geomorphologic
5.5 Conclusions

The results obtained in this chapter show that the geology of the Tabernas study area strongly controls the landscape formation (morphostructural units), the development of particular landforms and the associated morphodynamic processes (Section 5.2). Specific types of lithologic units, like the one formed by marls, sandstones and conglomerates (Tbc11–12), is characterized by the

Figure 5.16: Extent of geomorphologic units affected with land cover changes between 1956 and 1995.

The land cover class defined as “Seasonal Cultivation” has a wide distribution in the geomorphologic units with a total area of 2575.92 Ha and it contributes to 70.81% to the changes presented in the geomorphologic units. Particularly, 87.37% of the changes are present in the “Low Hills”, and 89.21% are present in the alluvial fans (Table 5.14).

Other types of land cover changes that present some extent in the geomorphologic units are those defined as “Sparse Bush and Grass Cover”, and “Sparse Bush Cover with Trees”. The first one has an extension of 418.48 Ha, which correspond to 11.50% and has a greater extension in the Alluvial Plains (161.6 Ha), Low Hills (110.76 Ha) and Alluvial Fans (74.92 Ha). The second one has an extension of 335.24 Ha that corresponds to 9.21% and presents greater extension in the units “Steep Relief of Sierra Alhamilla” (316.24 Ha) and “Low Hills” (9.52 Ha) (Table 5.14 and Figure 5.16).

From the information derived out of the overlay operations, it is clear that the land use and land cover classes that represent gross changes, such as “Dry Farming” and “Seasonal Cultivation”, are associated where certain type of morphologic conditions are met. In order to have areas suitable for agricultural activities, they must have low and nearly flat to undulating relief, with gentle and predominant straight slopes. The geomorphologic units “Low Hills”, “Alluvial Fans” and “Alluvial Plains” present those types of conditions, and it is why the changes take place in those specific morphologies.

5.5 Conclusions

• The results obtained in this chapter show that the geology of the Tabernas study area strongly controls the landscape formation (morphostructural units), the development of particular landforms and the associated morphodynamic processes (Section 5.2). Specific types of lithologic units, like the one formed by marls, sandstones and conglomerates (Tbc11–12), is characterized by the
formation of a badland type of landscape, and is highly susceptible to the development of geomorphologic processes such as rill and sheet erosion. Another example of these relationships occurs in the karstic landscape, which is restricted to gypsum and limestone lithologic units. The most predominant morphodynamic process affecting this particular landscape is the solution process.

- Human activities such as changes in land use, land cover pattern and road construction and development have affected the natural environment of the study area. In this chapter, it was established that the presence of morphodynamic processes and specific types of landforms have a close relationship with the human activities previously described.

- The changes in the land use class “Dry Farming” that has a spatial distribution quite similar to the land cover type “Seasonal Cultivation”, present a close association with the presence of morphodynamic processes; particularly sheet erosion (Sections 5.3.1 and 5.3.2). This occurs specially during the period between 1956 and 1981 when the major changes in the study area were detected. For the period between 1981 and 1995, the areas with land use and land cover changes that were affected by morphodynamic processes present less extension.

- The geomorphology have played an important role in the development of agricultural activities through time in the study area. The geomorphologic units “Low Hills”, “Alluvial Fans” and “Alluvial Plains” are the ones that favor in a great extent the land use and land cover changes (Sections 5.4.1 and 5.4.2). Particularly, most of the changes in the classes “Dry Farming” and “Seasonal Cultivation” have taken place in the described geomorphologic units.

- The morphodynamic processes are also related with the road construction and development (asphaltisation) in the Tabernas area (Section 5.3.3). Sheet erosion is the morphodynamic process that presents the greatest extent of area affecting the different types of roads from 1956 to 1995. Small areas of concentrated erosion, evidenced by the presence of rills and gullies, happened to be generated from the road construction between 1950 and 1985.

- This chapter also illustrates the usefulness of GIS overlay operations like “map-cross”. It facilitates the analysis of thematic maps and permits to establish relationships between them. In this case, the relationships between the components of the natural environment (geology, geomorphology and morphodynamic processes) and human activities (changes in land use and land cover pattern and the development of the asphaltisation process) were studied.
Chapter 6

Preliminary Assessment of Soil Pollution as an Indicator of Land Degradation

6.1 Introduction

This chapter describes the procedures followed to preliminary characterize the state of the soils in the area of Tabernas. The purpose of this characterization was to determine the heavy metal distribution and to what extent the presence of anomalous concentrations could be related to human activities or to natural processes. First, the methods, techniques and procedures to select the sites to carry out the sampling program, the sample preparation and the laboratory analysis are described. Then, an interpretation of the results obtained from the laboratory analyses are presented, as well as a comparison with standard parameters of soil quality to infer and evaluate whether some degree of pollution had taken place. Next, a relationship is established between the human activities (land use) in the study area and the heavy metal concentrations. At the end of the chapter conclusions about the state of the soils as an indicator of land degradation are presented.

6.2 Distribution of heavy metals in the soils

The Earth’s natural environment is composed by the lithosphere, the pedosphere, the atmosphere and the hydrosphere, which are considered as environmental reservoirs, [38] and [30]. Another component, the biosphere, is composed by the living organisms that inhabit the Earth and interact with the rest of the components. These components are in a constant exchange of matter and energy as a consequence of the natural and anthropogenic processes. The environmental functions that can be associated to the elements that compose the natural environment are: naturalness, source of resources, support of activities, hazards generator and sink of wastes [22] and [53].

The lithosphere is the original source of all metals. It is as the pedosphere, the hydrosphere and the atmosphere a sink for them. The natural interactions between the
6.2. Distribution of heavy metals in the soils

Environmental reservoirs conditions the metal transport and accumulation in the pedosphere. Several are the processes that represent these interactions, as the metals are produced in the geosphere, weathering, decomposition, chemical precipitation, lixiviation, adsorption, etc. influence the concentration and transport of the heavy metals to the pedosphere.

The pedosphere is formed by the soil and the geomorphologic units [30]. These two elements result from the interaction of the primary elements, e.g., lithosphere, hydrosphere, atmosphere and biosphere. Soil formation processes are controlled by several factors, e.g., parent materials, topography, climate, biological activity and time. There is a relationship of dependency between the environmental conditions of a particular place in the Earth and the influence that these factors exert in the processes that control the development of the pedosphere.

The factors that control the distribution of metals in the pedosphere are the abundance of elements in the parent rock and the nature of the weathering and soil-forming processes (physical, chemical reactions, biologic activity and time). This can be translated into three main criteria to associate the distribution of the metals: soil type, depth (soil horizon) and particle size. The anthropogenic activity is also an important factor that can exert a small or in some cases, a strong influence in the distribution, behaviour and concentration of the metals in the soils, e.g., acid mine drainage, industrialization, intensive agricultural activities.

Elevated concentrations of heavy metals in the soils pose a risk for soil, plants and groundwater pollution. These aspects present a close relationship with land degradation as the land becomes unproductive. For the characterization of contaminated sites, two approaches can be followed. One consists in the comparison of concentrations of heavy metals obtained analytically with soil quality standards. The other approach, consists in risk assessment; which requires a detailed soil information that is not always available, [55]. Lately, the use of a more reasonable methodology that combines the previous two has been used in Germany, Basque Country and Cataluña to evaluate contaminated sites and generate standard values as an instrument [55].

The advantage of the methodology based on quality standards is that a rapid assessment can be made at low costs with a few number of samples. It provides basic information about the contamination status of a given site. The disadvantages are that the procedures to obtain soil quality standards are not universally accepted. Also, the soil sampling schemes, the methods and protocols for laboratory analysis are not yet standardized; which creates difficulties to establish comparisons. The high dependency on soil characteristics and properties that controls the retention and mobility of contaminants; makes that the same quality standards can not be valid for all kind of soils [55]. The establishment of quality standards, based on relationships between soil properties such as texture, organic matter, pH, etc. has been an approach followed by some European countries, e.g., The Netherlands, Belgium, Basque Country in Spain, to overcome the difficulties of this approach [55].

The risk assessment approach implies a rational research process that includes four steps: hazard identification, exposure assessment, toxicity assessment, and risk characterization [55]. This series of steps requires previous characterization of the soil resources, pollutants and the establishment of standard values of toxicological data that are not always available. Even though this approach represents a complete assessment of the soil conditions, the necessity of information with a high level of
detail, the uncertainties to define reference doses for humans could be some of the main disadvantages of the approach, associated as well with the high costs and the requirement of specialized personnel [55].

In this study, the lack of previous information on the heavy metal concentration and other soil properties, as well as other constraints such as the associated costs, the amount of human resources, the time factor and uncertainties associated; do not permit to follow the risk assessment approach. Then, the methodology that has been followed to evaluate the soils of the Tabernas area is the comparison of the obtained values with soil quality standards developed for other areas.

6.3 Methods and Techniques

Techniques used to characterize heavy metals in soils and sediments can be categorized into two groups, selective extraction methods and instrumental surface analysis. Extraction methods have been applied extensively by soil scientists for metal analysis, leaching of metals from soils and sediments, nutrient availability for plants, and studies of fate and mobility of metals in the soil environment. These methods were developed on the assumption that it is possible to separate heavy metals present in soils and sediments into different geochemical phases [78].

In the Tabernas area, a preliminary characterization of the soils to determine their actual state was attempted. Soil properties were determined as a screening technique that permits to formulate further detailed investigations to have a complete characterization of the soil resource. This section describes the soil sampling procedures and the properties evaluated. The interpretation and analysis of the results of the soil properties, like the concentration of total and extractable metals will be a key element to accomplish the soil characterization.

6.3.1 Soil sampling procedures

In order to characterize and analyze the state of the heavy metals and other soil properties in the Tabernas area, a random sampling schema was designed. The reason to sample in a random manner, is supported by the fact that there are no previous studies that show the concentration of heavy metals in the soils of the study area. Also, the sampling area was concentrated in the valleys and piedmonts where most of the human activities are concentrated and there is certain homogeneity, according to the soil formation processes, in the alluvio–colluvial soils. Therefore, the random sampling is justified as a screening procedure, to have a general idea, as a preliminary approach to characterize the soil conditions. The obtained results aim to select particular areas of interest where further sampling and analysis should be carried out next.

The soil sampling was carried out during the end of September and the beginning of October (2001). The weather conditions were variable, generally with dry weather and also with a few rainy days. The total number of sampled sites was 21 and their spatial distribution and the land use associated is presented in Figure 6.1.

All the soil samples were collected from the upper surface horizon at a depth between 0 and 20 cm. This criterion obeyed to identify the sources of pollution and
Figure 6.1: Soil sampling sites and land uses associated. Source of land use map (2).

the possibility to find relationships with human activities, specifically those related with agricultural practices. The results will permit to extend the sampling to the soil profile if significant values of contamination are found. Also, to characterized the area to establish the background values; the soil horizon “C” would be a sampling target. This is very important because it permits to separate natural concentrations from those resulted from the human activities.

The samples consisted of approximately 500 g of soil, sieved to a particle size of less than 2 mm. They were stored and sealed in polyethylene bags with a capacity of 2 Kg. They were labelled starting from the first one JP01, up to JP19. In the case of sample JP03, two samples (JP03a and JP03b) were taken due to the existence of a lithologic contact with different soil characteristics at the sampling site. The use of metal tools was avoided and a plastic scoop was used to reduce possible sources of contamination.

The sample preparation for laboratory analysis consisted in air drying at room temperature for 3 days, particle size reduction, weighting and storing the required amount of sample for the different types of analyses. Most of the laboratory analysis required a particle size of less than 2 mm. The analysis of total metal determination required the reduction of the particle size to 80 mesh (0.187 mm).

The information collected for each sampling site consisted in: sample and parcel identification, parcel description and field observations (e.g. soil structure, presence of stones, biological activity and root depth). The field information and the laboratory results were entered into a relational database designed to store and manage the soil information. The database has a simple structure of one level and is composed of seven tables. The “station” and six more tables, “parcel identification”, “parcel description”, “field tests”, “conventional analysis”, “total metals” and “extractable metals”. All the tables are linked to the table “station” in a one to
many relationships shown in Figure 6.2. The database was created in M.S ACCESS and the “station” table was imported to “dbase” format to facilitate further GIS integration of the primary field and laboratory data.

### 6.3.2 Laboratory analyses

The laboratory analyses were conducted to perform a preliminary evaluation of the state of the soils in the study area. Chemical and physical soil properties were measured to obtain values that might be related and extrapolated to infer the degree of pollution by the concentration of heavy metals. The selected soil properties to be measured by laboratory analysis were divided into two groups:

- **Total and EDTA-extractable concentrations of some heavy metals**: Cu, Ni, Cd, Pb, Mn, Zn, As and Fe (Non heavy metal).

- **Conventional analysis**: pH, electric conductivity, cation exchange capacity, particle size and organic carbon content.

The soil analyses were carried out at the geochemical laboratory of ITC. The procedures and methods that were followed correspond to standard protocols adopted from the International Soil Reference and Information Centre (ISRIC), [71] and the Canadian Association of Soil Science [26]. For the total and extractable metals content, the protocols used at the “Centro de Estudios sobre Desertificacion, CIDE” in Valencia, Spain, were followed. Detailed descriptions of the laboratory procedures, although very important, is out of the scope of this study and the reader is referred to the sources presented for each analysis.

**Total metal content**

To analyze the total metal content, the soil samples were pulverized up to a particle size of 80-mesh, which is equivalent to 0.187 mm. A similar procedure used at CIDE [16] and presented in Figure 6.3 was followed.

An indirect and relative determination of the carbonate content of the samples was also obtained by the visual inspection of the reaction at the moment of adding the HClO$_4$. It was determined that samples JP03b, JP05, JP06, JP16 and JP19 presented a high carbonate content. From this group of samples, sample JP16 presented the highest content as indicated by a violent reaction with the acid.

Total Cu, Ni, Cd, Pb, Mn, Zn and As and Fe concentrations were determined by measuring extract solutions by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Standard solutions and good calibration curves for each element were reported from the analysis. Then, the accuracy levels were acceptable to measure the metal concentrations in the samples. Two replicate samples (JP07 and JP15) were selected for this analysis.

The results are presented in Table 6.1. The exact concentration for Cd were not reported, but all the values are below 0.1 ppm. Statistics like mean, standard deviation, maximum and minimum values were calculated for the analyzed elements. In general, the soils of Tabernas area do not show exceptionally high concentrations of
Figure 6.2: Database structure generated to store and manage the soils information.
6.3. Methods and Techniques

1 gr. powder soil
(0.2 mm.)
+ 10 mL HNO3 70%.

12 hours (1 night)

10 mL HNO3 conc.
+ 3 mL HClO4 conc.

Residue
+ 4 mL HCl 6M a 120°C
(hot)

Centrifuge for 5 min at 4000 r.p.m.

The extract is levelled up to
50 mL with deionized water

Keep in plastic
bottle at 4°C

Inductively Coupled Plasma
Atomic Emission Spectrometry

Figure 6.3: Flow chart of the procedure to determine the total metal concentration (16).
6.3. Methods and Techniques

Table 6.1: Total metal in soil samples from the Tabernas study area. The concentrations are in (\%) for Fe and ppm for the rest of elements. For Cd, the obtained values were reported below 0.1 ppm.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP 01</td>
<td>16.3</td>
<td>247.7</td>
<td>25.1</td>
<td>33.5</td>
<td>40.4</td>
<td>3.1</td>
<td>0.56</td>
</tr>
<tr>
<td>JP 02</td>
<td>24.1</td>
<td>438.5</td>
<td>24.9</td>
<td>43.4</td>
<td>47.7</td>
<td>2.98</td>
<td>0.74</td>
</tr>
<tr>
<td>JP 03a</td>
<td>26.1</td>
<td>203.4</td>
<td>33.5</td>
<td>21.3</td>
<td>47.7</td>
<td>4.01</td>
<td>1.24</td>
</tr>
<tr>
<td>JP 03b</td>
<td>21.5</td>
<td>183.9</td>
<td>22.3</td>
<td>19.9</td>
<td>34.6</td>
<td>2.44</td>
<td>0.51</td>
</tr>
<tr>
<td>JP 04</td>
<td>26.2</td>
<td>245.5</td>
<td>22.2</td>
<td>30.7</td>
<td>47.1</td>
<td>2.73</td>
<td>0.49</td>
</tr>
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<td>JP 05</td>
<td>22.7</td>
<td>426.2</td>
<td>27.7</td>
<td>66.3</td>
<td>72.4</td>
<td>3.07</td>
<td>0.64</td>
</tr>
<tr>
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<td>19</td>
<td>327.8</td>
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<td>51.8</td>
<td>3.06</td>
<td>0.93</td>
</tr>
<tr>
<td>JP 07</td>
<td>25.8</td>
<td>270.2</td>
<td>31.6</td>
<td>15.8</td>
<td>59.6</td>
<td>3.16</td>
<td>0.50</td>
</tr>
<tr>
<td>JP 07-I</td>
<td>20.9</td>
<td>266.1</td>
<td>31.3</td>
<td>16.6</td>
<td>57.2</td>
<td>3.18</td>
<td>0.53</td>
</tr>
<tr>
<td>JP 08</td>
<td>29.4</td>
<td>300.8</td>
<td>43.1</td>
<td>10.3</td>
<td>82.8</td>
<td>3.98</td>
<td>0.76</td>
</tr>
<tr>
<td>JP 09</td>
<td>32.6</td>
<td>333</td>
<td>47.1</td>
<td>15.6</td>
<td>89.8</td>
<td>4.4</td>
<td>0.98</td>
</tr>
<tr>
<td>JP 10</td>
<td>40.7</td>
<td>373.8</td>
<td>40</td>
<td>23.4</td>
<td>68</td>
<td>3.59</td>
<td>1.12</td>
</tr>
<tr>
<td>JP 11</td>
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<td>463.7</td>
<td>52.9</td>
<td>16.2</td>
<td>99.1</td>
<td>4.64</td>
<td>1.09</td>
</tr>
<tr>
<td>JP 12</td>
<td>36.3</td>
<td>442.2</td>
<td>52.6</td>
<td>13.9</td>
<td>98.3</td>
<td>4.65</td>
<td>1.44</td>
</tr>
<tr>
<td>JP 13</td>
<td>52.5</td>
<td>473.9</td>
<td>49</td>
<td>50.1</td>
<td>86.6</td>
<td>4.75</td>
<td>1.13</td>
</tr>
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<td>16.9</td>
<td>89.6</td>
<td>4.45</td>
<td>1.10</td>
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<td>51.4</td>
<td>3.07</td>
<td>0.56</td>
</tr>
<tr>
<td>JP 15-I</td>
<td>21.9</td>
<td>281.3</td>
<td>29.3</td>
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<td>54.1</td>
<td>3.15</td>
<td>0.56</td>
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<td>JP 16</td>
<td>18.2</td>
<td>186.8</td>
<td>23.1</td>
<td>28</td>
<td>38.2</td>
<td>2.48</td>
<td>0.58</td>
</tr>
<tr>
<td>JP 17</td>
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<td>269.4</td>
<td>31.8</td>
<td>12.7</td>
<td>59.4</td>
<td>3.22</td>
<td>0.66</td>
</tr>
<tr>
<td>JP 18</td>
<td>47.5</td>
<td>497</td>
<td>57.5</td>
<td>16.6</td>
<td>101.8</td>
<td>4.92</td>
<td>1.38</td>
</tr>
<tr>
<td>JP 19</td>
<td>224.4</td>
<td>283</td>
<td>37</td>
<td>17.7</td>
<td>140.1</td>
<td>3.92</td>
<td>0.43</td>
</tr>
<tr>
<td>JP 20</td>
<td>46</td>
<td>299.7</td>
<td>31.3</td>
<td>27</td>
<td>64.2</td>
<td>3.16</td>
<td>0.36</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Error</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Sample Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>37.98</td>
<td>8.72</td>
<td>32.6</td>
<td>41.82</td>
<td>1749.32</td>
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<tr>
<td>Mn</td>
<td>324.70</td>
<td>19.66</td>
<td>299.7</td>
<td>94.28</td>
<td>8888.23</td>
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<tr>
<td>Ni</td>
<td>35.41</td>
<td>2.28</td>
<td>31.6</td>
<td>10.94</td>
<td>119.66</td>
</tr>
<tr>
<td>Pb</td>
<td>24.38</td>
<td>2.91</td>
<td>17.0</td>
<td>13.95</td>
<td>194.52</td>
</tr>
<tr>
<td>Zn</td>
<td>68.78</td>
<td>5.40</td>
<td>17.7</td>
<td>25.91</td>
<td>671.43</td>
</tr>
<tr>
<td>Fe</td>
<td>0.57</td>
<td>0.16</td>
<td>59.6</td>
<td>0.76</td>
<td>0.58</td>
</tr>
<tr>
<td>As</td>
<td>0.80</td>
<td>0.07</td>
<td>31.3</td>
<td>0.32</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The average content of minor and trace elements in soils were compiled by [39]. The proposed concentrations are useful indicators of background values that might be expected in areas that do not contain mineralization. Table 6.2 presents the standard values proposed by [39] and the maximum concentration obtained for the elements in the analysis of the Tabernas soils. Even though this comparison can be very general due to the fact that local conditions of geology, climate and weathering exert a strong influence in the metals distribution in soils, it is used as an indication of the relative concentration of the elements in the soils. In Section 6.4, a comparison of the metal distribution with values obtained for similar environmental conditions will be established.

heavy metals that permit to infer abnormal values except for the Cu concentration in sample JP19, which is relatively high.

The average content of minor and trace elements in soils were compiled by [39]. The proposed concentrations are useful indicators of background values that might be expected in areas that do not contain mineralization. Table 6.2 presents the standard values proposed by [39] and the maximum concentration obtained for the elements in the analysis of the Tabernas soils. Even though this comparison can be very general due to the fact that local conditions of geology, climate and weathering exert a strong influence in the metals distribution in soils, it is used as an indication of the relative concentration of the elements in the soils. In Section 6.4, a comparison of the metal distribution with values obtained for similar environmental conditions will be established.
Table 6.2: Standard values for total metal concentrations (ppm) in soils presented by (39) and maximum values obtained for the Tabernas soils.

<table>
<thead>
<tr>
<th>Element</th>
<th>Avg. Value in Soils</th>
<th>Max. Value in Tabernas</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>1 - 50</td>
<td>1.44</td>
</tr>
<tr>
<td>Cd</td>
<td>1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Cu</td>
<td>2 - 100</td>
<td>224.40</td>
</tr>
<tr>
<td>Mn</td>
<td>850</td>
<td>497</td>
</tr>
<tr>
<td>Ni</td>
<td>5 - 500</td>
<td>57.50</td>
</tr>
<tr>
<td>Pb</td>
<td>2 - 200</td>
<td>66.30</td>
</tr>
<tr>
<td>Zn</td>
<td>10 - 300</td>
<td>140.10</td>
</tr>
</tbody>
</table>

The results of the concentrations of total metal were used to optimize the analysis of extractable metals, particle size and organic carbon content. Six samples with the highest metal concentrations were selected to performed the analysis. The samples correspond to the label: JP05, JP11, JP12, JP16, JP18 and JP19.

**Extractable metals**

To determine the fraction of extractable metals in the soil samples, a procedure using EDTA (ethylenediaminetetraacetic acid) was followed according to the protocols used at CIDE, [16] shown in Figure 6.4. EDTA is a weak organic acid with complexing and chelating ability to sequester divalent and trivalent cations. It has commonly been used in soil analysis to determine plant-available micronutrients, specially copper, iron, manganese and zinc. It extracts metals on exchange sites of both inorganic and organic complexes in soils and sediments, without attack on the crystal structure of silicate minerals and releases metals associated with hydromorphically moved materials [74], [9] and [10] in [14].

The objective of performing a selective extraction is to isolate and quantify that portion of an element in a sample that is relatively loosely bound, indicating prior mobility [25]. In a general sense, the extractable metals are the fraction of the total concentration of metals in the soil that are mobile and then can reach the vegetation or pass to the groundwater.

Extractable Cu, Ni, Cd, Mn, Zn, As and Fe concentrations were also determined, as in the total metal content, by measuring extract solutions by inductively coupled plasma atomic emission spectrometry (ICP-AES). Two replicate samples, JP05, and JP19, were selected in this analysis. The obtained results and some statistics for the analyzed elements are presented in Table 6.3.

The results show that the EDTA-extractable metals are in a range between 1 and 19% of the total metal concentrations; but average values do not exceed the 10%. For As, one sample was below the detection limit and abnormal values were obtained for most of the samples as they exceed the value of total As. In general, the results for the EDTA-extractable metals are relatively low, even for the sample JP19 with a high value of total Cu, the extractable concentration obtained only represents 1% (Table 6.3). These results do not permit to infer a significant amount of mobile heavy
6.3. Methods and Techniques

Figure 6.4: Flow chart of the procedure to determine the extractable metals concentration (16).
6.3. Methods and Techniques

Table 6.3: Concentrations in (ppm) of extractable (Extr) and percentage of the total metals (%Tot.) in soil samples from the Tabernas study area.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extr. %Tot Extr. %Tot Extr. %Tot Extr. %Tot Extr. %Tot Extr. %Tot Extr. %Tot Extr. %Tot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP-05</td>
<td>4.3 19</td>
<td>10.4 6</td>
<td>1.5 4</td>
<td>3.2 4</td>
<td>87.0 0.07</td>
<td>0.7 115</td>
<td>0.1</td>
</tr>
<tr>
<td>JP-11</td>
<td>3.1 8</td>
<td>32.3 7</td>
<td>2.5 5</td>
<td>2.7 3</td>
<td>49.7 0.11</td>
<td>0.7 63</td>
<td>0.03</td>
</tr>
<tr>
<td>JP-12</td>
<td>1.9 5</td>
<td>31.1 7</td>
<td>1.4 3</td>
<td>0.7 1</td>
<td>37.2 0.06</td>
<td>-0.4 26</td>
<td>0</td>
</tr>
<tr>
<td>JP-16</td>
<td>2.4 13</td>
<td>4.0 2</td>
<td>0.9 4</td>
<td>1.2 3</td>
<td>3.3 0.01</td>
<td>1.6 272</td>
<td>0.02</td>
</tr>
<tr>
<td>JP-18</td>
<td>3.1 6</td>
<td>36.4 7</td>
<td>1.0 2</td>
<td>1.0 1</td>
<td>35.1 0.07</td>
<td>0.4 26</td>
<td>0.01</td>
</tr>
<tr>
<td>JP-19</td>
<td>1.9 1</td>
<td>5.5 2</td>
<td>1.9 5</td>
<td>0.8 1</td>
<td>6.9 0.02</td>
<td>0.3 69</td>
<td>0.02</td>
</tr>
<tr>
<td>JP-11 I</td>
<td>3.3 14</td>
<td>32.6 7</td>
<td>0.9 2</td>
<td>2.8 3</td>
<td>51.5 0.11</td>
<td>0.0 3</td>
<td>0.02</td>
</tr>
<tr>
<td>JP-19 I</td>
<td>1.9 1</td>
<td>5.5 2</td>
<td>0.8 2</td>
<td>0.8 1</td>
<td>6.3 0.02</td>
<td>1.6 363</td>
<td>0.02</td>
</tr>
<tr>
<td>Mean</td>
<td>2.7</td>
<td>20.8</td>
<td>1.3</td>
<td>1.6</td>
<td>26.4</td>
<td>0.6</td>
<td>0.03</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.3</td>
<td>5.0</td>
<td>0.2</td>
<td>0.4</td>
<td>7.0</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Median</td>
<td>2.7</td>
<td>25.3</td>
<td>1.0</td>
<td>1.1</td>
<td>28.1</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.9</td>
<td>14.0</td>
<td>0.6</td>
<td>1.0</td>
<td>19.7</td>
<td>0.7</td>
<td>0.03</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.7</td>
<td>196.3</td>
<td>0.4</td>
<td>1.1</td>
<td>388.2</td>
<td>0.5</td>
<td>0.00</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.9</td>
<td>4.0</td>
<td>0.8</td>
<td>0.7</td>
<td>3.3</td>
<td>-0.4</td>
<td>0.00</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.3</td>
<td>36.4</td>
<td>2.5</td>
<td>3.2</td>
<td>51.5</td>
<td>1.6</td>
<td>0.10</td>
</tr>
</tbody>
</table>

metals available to the plants of groundwater system; regardless that the tolerance levels for the vegetation and use of groundwater in the study area are not available.

pH

The pH is a numerical expression of the relative acidity or alkalinity of an aqueous system. The procedure followed corresponds to the method presented in [71]. It consists in the determination of the pH in a 1:2.5, soil:water suspension. The results and some statistical values obtained for the measurement are presented in Table 6.4.

From the 21 samples analyzed, a median of 8.27 and maximum and minimum values of 9.7 and 7.6 respectively were obtained. The minimum and maximum values, suggest that the soils can be classified as slightly alkaline and very strong alkaline according to the classes presented in (http://www.statlab.iastate.edu/soils/ssm/chap3ca.html).

Electrical conductivity

The electrical conductivity (Ec) is a numerical expression of the inherent ability of a medium to carry an electric current. It is commonly used as an expression of the total dissolved salt concentration of an aqueous sample. In the International System of Units, The Ec is reported as siemens per meter (S/m) or decisiemens per meter (dS/m).

The Ec was measured in a 1:5, soil:water suspension. The results are presented in Table 6.4. According to the classification of the degree of soil salinity based on the Ec (http://www.statlab.iastate.edu/soils/ssm/chap3ca.html), all the samples are non-saline. Only one sample, (JP16), presents the Ec value close to the threshold level between non-saline and very slightly saline, which is 2 dS/m.

Cation exchange capacity

A soil’s Cation Exchange Capacity (CEC) is a measure of its ability to adsorb cations. It is expressed in milliequivalent of the adsorbed cation per 100 grams of the
Table 6.4: Results and statistics for the determination of pH and Ec (in dS/m).

<table>
<thead>
<tr>
<th>SAMPLE ID</th>
<th>pH</th>
<th>Ec</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP01</td>
<td>7.9</td>
<td>0.22</td>
</tr>
<tr>
<td>JP02</td>
<td>8.1</td>
<td>0.21</td>
</tr>
<tr>
<td>JP03a</td>
<td>8.7</td>
<td>0.77</td>
</tr>
<tr>
<td>JP03b</td>
<td>8</td>
<td>1.09</td>
</tr>
<tr>
<td>JP04</td>
<td>8.1</td>
<td>0.25</td>
</tr>
<tr>
<td>JP05</td>
<td>8</td>
<td>0.22</td>
</tr>
<tr>
<td>JP06</td>
<td>7.9</td>
<td>0.33</td>
</tr>
<tr>
<td>JP07</td>
<td>9.2</td>
<td>0.24</td>
</tr>
<tr>
<td>JP08</td>
<td>8.3</td>
<td>0.19</td>
</tr>
<tr>
<td>JP09</td>
<td>7.8</td>
<td>0.11</td>
</tr>
<tr>
<td>JP10</td>
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<td>0.65</td>
</tr>
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<td>JP11</td>
<td>7.6</td>
<td>0.17</td>
</tr>
<tr>
<td>JP12</td>
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<td>0.08</td>
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<td>JP13</td>
<td>7.8</td>
<td>0.26</td>
</tr>
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<td>JP14</td>
<td>8.1</td>
<td>0.17</td>
</tr>
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<td>JP15</td>
<td>9.4</td>
<td>0.46</td>
</tr>
<tr>
<td>JP16</td>
<td>8.1</td>
<td>1.6</td>
</tr>
<tr>
<td>JP17</td>
<td>8</td>
<td>0.33</td>
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<tr>
<td>JP18</td>
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<td>0.16</td>
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<tr>
<td>JP19</td>
<td>8.3</td>
<td>0.16</td>
</tr>
<tr>
<td>JP20</td>
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<td>0.35</td>
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<tr>
<td>Mean</td>
<td>8.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>Median</td>
<td>8.1</td>
<td>0.24</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.6</td>
<td>0.37</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.3</td>
<td>0.14</td>
</tr>
<tr>
<td>Minimum</td>
<td>7.6</td>
<td>0.08</td>
</tr>
<tr>
<td>Maximum</td>
<td>9.7</td>
<td>1.60</td>
</tr>
</tbody>
</table>
6.3. Methods and Techniques

clay (meq/100 g), or centi-moles per kilogram (cmol (+)/Kg) [39].

The CEC of clay minerals enables large amounts of certain elements, including some metals, to be adsorbed. In most cases, the CEC increases with pH and thus, at low pH values, little adsorbed metal will be found on clay minerals [39]. Particle size, surface area, amount of soil moisture, degree of crystallinity, and other factors all affect the ability of clay minerals to adsorb metals [39]. However, there is convincing evidence to indicate that it is manganese and iron oxy-hydroxides found in soils and sediments, which are the controlling factors in the fixation of the important heavy metals (Zn, Cu, Ni, Co), as will be discussed in Section 6.4, rather than the clay minerals [35] in [39].

A procedure to calculate the exchangeable cations and the CEC that uses an extraction with BaCl$_2$, presented in [26] was followed. In this method, the CEC is calculated as the sum of exchangeable cations (Ca, Mg, K, Na, Al, Fe and Mn). The exchangeable cations were measured by inductively coupled plasma atomic emission spectrometry (ICP-AES). The obtained values for Fe and Mn were below the detection limit indicating very low values for these two cations. Therefore, their contribution to the CEC was considered negligible.

There were some constraints in the results of the analysis of the CEC. The method followed presents some limitations for saline soils and those with high contents of gypsum. The reaction between the Barium Chloride (BaCl$_2$) and the gypsum (CaSO$_4$) will consume the SO$_4$ increasing the concentration of calcium. This was found in the results of the analysis of the concentrations of exchangeable cations by inductively coupled plasma atomic emission spectrometry (ICP-AES) Table 6.5 shows high values for Ca in all samples, specially in JP01 to JP06, JP10, JP16, JP17, JP19 and JP20. High values were also observed for Mg and Na cations, indicating some salts concentration in few samples.

The contribution of each exchangeable cation and the effective CEC, defined as the sum of individual contribution, were calculated. The obtained values were recalculated based on the clay content and extremely high values were obtained. Then, this method was considered not suitable for this specific type of soils and a low reliability may be expected from the results.

**Particle size distribution**

The particle size analysis consists in the separation of the mineral part of the soil into various size fractions and the determination of the proportions of these fractions [71]. The analysis consists of the determination of gravel and coarse materials, but the procedure followed according to [71] only deals with the analysis of fine earth, which are the particle sizes of less than 2 mm (sand, silt and clay fractions).

The procedure is very extensive and elaborate. It involves many steps and includes the oxidation of the organic matter using H$_2$O$_2$ (hydrogen peroxide), the removal of carbonate content (specifically for sample JP16) using acetic acid and the separations of the individual fractions. The reader is referred to [71] for the complete details and the calculations involved to obtained the sand, silt and clay fractions of the analyzed samples.

The results of the analysis and the statistics calculated are presented in Table 6.6. The texture of all samples was classified as “sandy loam” according to the classifica-
Table 6.5: Concentrations (in ppm) of the exchangeable cations measured to calculate CEC. It can be observed the high values for Ca, Na and Mg in some samples.

<table>
<thead>
<tr>
<th>SAMPLE ID</th>
<th>Al</th>
<th>Ca</th>
<th>K</th>
<th>Mg</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP01</td>
<td>190</td>
<td>12391</td>
<td>32</td>
<td>939</td>
<td>413</td>
</tr>
<tr>
<td>JP02</td>
<td>103</td>
<td>12391</td>
<td>744</td>
<td>1187</td>
<td>198</td>
</tr>
<tr>
<td>JP03a</td>
<td>52</td>
<td>12399</td>
<td>1801</td>
<td>4622</td>
<td>10618</td>
</tr>
<tr>
<td>JP03b</td>
<td>175</td>
<td>12393</td>
<td>631</td>
<td>1689</td>
<td>8572</td>
</tr>
<tr>
<td>JP04</td>
<td>257</td>
<td>9771</td>
<td>2488</td>
<td>789</td>
<td>346</td>
</tr>
<tr>
<td>JP05</td>
<td>107</td>
<td>12402</td>
<td>1185</td>
<td>941</td>
<td>235</td>
</tr>
<tr>
<td>JP06</td>
<td>292</td>
<td>12401</td>
<td>890</td>
<td>909</td>
<td>323</td>
</tr>
<tr>
<td>JP07</td>
<td>58</td>
<td>6585</td>
<td>1011</td>
<td>2483</td>
<td>3592</td>
</tr>
<tr>
<td>JP08</td>
<td>78</td>
<td>5563</td>
<td>413</td>
<td>754</td>
<td>403</td>
</tr>
<tr>
<td>JP09</td>
<td>160</td>
<td>3078</td>
<td>988</td>
<td>561</td>
<td>160</td>
</tr>
<tr>
<td>JP10</td>
<td>70</td>
<td>7619</td>
<td>554</td>
<td>3111</td>
<td>16875</td>
</tr>
<tr>
<td>JP11</td>
<td>190</td>
<td>4980</td>
<td>688</td>
<td>1063</td>
<td>80</td>
</tr>
<tr>
<td>JP12</td>
<td>87</td>
<td>4237</td>
<td>255</td>
<td>621</td>
<td>133</td>
</tr>
<tr>
<td>JP13</td>
<td>125</td>
<td>6572</td>
<td>1149</td>
<td>443</td>
<td>158</td>
</tr>
<tr>
<td>JP14</td>
<td>90</td>
<td>5478</td>
<td>287</td>
<td>499</td>
<td>176</td>
</tr>
<tr>
<td>JP15</td>
<td>130</td>
<td>6746</td>
<td>801</td>
<td>2972</td>
<td>5729</td>
</tr>
<tr>
<td>JP16</td>
<td>120</td>
<td>12394</td>
<td>752</td>
<td>1974</td>
<td>16108</td>
</tr>
<tr>
<td>JP17</td>
<td>145</td>
<td>8064</td>
<td>698</td>
<td>2096</td>
<td>399</td>
</tr>
<tr>
<td>JP18</td>
<td>110</td>
<td>6015</td>
<td>345</td>
<td>553</td>
<td>528</td>
</tr>
<tr>
<td>JP19</td>
<td>82</td>
<td>5163</td>
<td>382</td>
<td>651</td>
<td>61</td>
</tr>
<tr>
<td>JP20</td>
<td>198</td>
<td>7036</td>
<td>722</td>
<td>2306</td>
<td>2497</td>
</tr>
</tbody>
</table>
6.4 Evaluation of the Results

Table 6.6: Results and statistics obtained for particle size, organic carbon and organic matter content.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>% Carbon</th>
<th>% Org. Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP-05</td>
<td>71.22</td>
<td>19.00</td>
<td>9.78</td>
<td>0.69</td>
<td>1.38</td>
</tr>
<tr>
<td>JP-11</td>
<td>84.51</td>
<td>13.49</td>
<td>2.00</td>
<td>0.86</td>
<td>1.72</td>
</tr>
<tr>
<td>JP-12</td>
<td>81.85</td>
<td>17.40</td>
<td>0.76</td>
<td>0.17</td>
<td>0.34</td>
</tr>
<tr>
<td>JP-16</td>
<td>69.56</td>
<td>24.93</td>
<td>5.50</td>
<td>0.69</td>
<td>1.38</td>
</tr>
<tr>
<td>JP-18</td>
<td>81.03</td>
<td>17.95</td>
<td>1.01</td>
<td>0.26</td>
<td>0.52</td>
</tr>
<tr>
<td>JP-19</td>
<td>84.17</td>
<td>11.80</td>
<td>4.03</td>
<td>0.69</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Mean 78.72 17.43 3.85 0.56 1.12
Standard Error 2.70 1.88 1.40 0.11 0.23
Median 81.44 17.68 3.01 0.69 1.38
Standard Deviation 6.61 4.61 3.43 0.28 0.55
Sample Variance 43.69 21.25 11.80 0.08 0.30
Minimum 69.56 11.80 0.76 0.17 0.34
Maximum 84.51 24.93 9.78 0.86 1.72

Organic matter and organic carbon content

The organic matter is also an important factor in the adsorption of certain elements, although diverse opinions exists as to its importance in comparison with the oxy-hydroxides of Fe and Mn [39]. The procedure followed to determine the percentage of organic matter from the organic carbon content is known as the Walkley-Black method [71]. It consists on a wet combustion of the organic matter with a mixture of potassium dichromate and sulphuric acid at about 125°C. The complete procedure and the calculations can be found in [71].

The results from the analysis and the statistics calculated in Table 6.6 show that the samples analyzed present very low values for carbon and organic matter content. The maximum values obtained are 0.86% for carbon and 1.72% of organic matter contents.

6.4 Evaluation of the Results

This section integrates the results of the laboratory analysis to characterize the state of the soils of the Tabernas area. Different studies [36] and [3] have defined standards related to background, thresholds and intervention values for total metal concentrations that permit to characterized contaminated sites. The standards are defined for total metal concentrations due to the complexity to determine standards for the extractable fractions, as they are conditioned for the amount of the total metal. An evaluation of these results and a comparison with the described standards will be presented. This was preferred instead of following the risk assessment methodology, due to the constraints and limitations for this study discussed in Section 6.2.

The levels of contamination by heavy metals and other toxic substances in the
6.4. Evaluation of the Results

Table 6.7: Background and reference concentration levels in (ppm) for heavy metals in soils from Cataluña, The Netherlands, United Kingdom and Canada ([36] and [3]).

<table>
<thead>
<tr>
<th>Metals</th>
<th>Spain</th>
<th>European Union</th>
<th>United Kingdom</th>
<th>Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cataluña</td>
<td>The Netherlands</td>
<td>United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>5</td>
<td>250</td>
<td>700</td>
<td>1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1.5</td>
<td>3.5</td>
<td>70</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>55</td>
<td>270</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>Nickel</td>
<td>49</td>
<td>250</td>
<td>700</td>
<td>50</td>
</tr>
<tr>
<td>Lead</td>
<td>70</td>
<td>300</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>Zinc</td>
<td>178</td>
<td>450</td>
<td>3000</td>
<td>200</td>
</tr>
</tbody>
</table>

1 Background values for Cataluña.
2 This value was deduced from the analytical data obtained in the so called “clean soils” of the Low Countries. Called reference value and nowadays is known as “diana value”. It is the concentration of contaminants that should not be exceeded for anthropogenic activities following a prevention policy (1986).
3 Overcoming B values indicates a high deviation from what is consider a standard soil (10% of organic matter and 25% of clay content). Detailed investigations must be followed (1986).
4 Concentrations higher that C value indicates that a “serious hazard for public health or the environment” if all the exposition paths are active. Overcoming C values indicates that a detailed investigation for soil restoration must be followed (1986).
5 Standards for Soil Environmental Quality (1991). They are based in ecological functions of soils and “diana and target values (TV)” are included. The values are equivalent to the maximum risk level permitted, and intend to evaluate the environmental quality during a specific period of time.

Soils should be defined taking into consideration the particular conditions of the natural environment of the study area. For the Tabernas area and even at the regional level of the Province of Andalucía, previous studies of soil characterization regarding the heavy metal concentration are not available at the moment. For Spain, surveys of this type have been developed at a regional level in the Basque Country and Cataluña Region [36]. Both regions are located in the north-east side of the country and the environmental conditions are similar. More recently, a soil survey has been started in the “Comunidad Valenciana”. The main objective is to characterize the soils including the content of heavy metals to define background and contamination values.

Countries like The Netherlands, The United Kingdom and Canada, have established background, threshold and intervention values as a reference to evaluate the level of contamination according to the different land uses [3]. Table 6.7 present those values, including the background levels established for the Cataluña region.

The concentrations obtained from the laboratory analyses close to the values defined for the for the Cataluña region will be more indicative of the existence of anomalous values. This is supported by the fact that the environmental conditions between Tabernas and Cataluña are more similar than countries like The Netherlands, United Kingdom and Canada. The comparison of the obtained values with the ones defined for these countries are taken only as a reference.

The overall results obtained for the total metal concentration of the soil samples analyzed, compared with the standards (Table 6.7) indicate relatively low values except for nine samples that exceed the background concentration defined for Cataluña and the cited countries. Those samples correspond to the ones identified as: JP05,
6.4. Evaluation of the Results


The concentrations of As and Cd are very low compared with the standards and do not exceed the established background values. For Pb, none of the samples present concentrations higher than the value established for Cataluña. The sample JP05 presents a concentration of 66.3 ppm. is located quite close (few meters) from the road CN-340. This fact may have certain incidence in this value.

In the case of Cu, the values of most of the samples are below the background levels in the four selected regions. The sample JP19 presents the highest value with 224 ppm. This sample exceeds the background value of Cataluña, the $A^2$ and $A^3$ values of the Netherlands, the threshold value of United Kingdom and the background, agricultural and residential use of Canada.

The obtained concentrations of Zn reflects normal conditions as it is very low compared with the background value established for Cataluña. The mean value is 68.78 ppm and it slightly exceeds the background concentrations established for Canada (60 ppm). The maximum value, 140.1 ppm (sample JP19) only overcomes in 0.1 ppm, the maximum risk of level allowed in The Netherlands (140 ppm). It also, overcomes the threshold level defined for United Kingdom (130 ppm).

The obtained concentrations for Ni in samples JP09, JP11 to JP14 and JP18 are very close or slightly overcome the background values for Cataluña and the $A^2$ value for The Netherlands. All samples present concentrations above the background value established for Canada and the threshold level for United Kingdom.

For Mn, the highest values of the analyzed samples represent half of the concentration defined by [39] (Table 6.2). However, it will be presented in Section 6.4.1 that this element and Fe play an important role in the concentration of other metals.

The results presented above for the total and EDTA-extractable concentrations of heavy metals in the soils of Tabernas seem to indicate that there is no evidence of soil pollution in the sampled area. However, in some points, there were values that exceed the background concentrations established for the Cataluña Region, which is an environment relatively similar to the study area, indicating anomalous values that can be investigated. A further sampling would permit to clarify the situation and even to refine the observations when background values are available for Tabernas or at least at a regional level of Andalucía.

6.4.1 Inter-element correlation

As an approach to generate additional information to understand the behaviour of the metals in the soils and to explain the concentration levels obtained for the heavy metals analyzed, correlation matrices for total and EDTA-extractable metals were calculated. This was attempted despite the limited number of samples that poses a constrain in the interpretations. Consequently the statistical significance of the results and the relationships that can be established have to be interpreted carefully, specially for the extractable metals.

The sample JP19 was excluded to calculate the correlation matrix for total metal concentrations. It was considered as an outlier because it was the only one with the highest values of Cu and Zn among the rest of the samples. From Table 6.8, it can be established that most of the elements present positive correlation factors except for Pb. The coefficients range from 0.54 to 0.97. The most significant positive correlation
between two metals is presented for Fe–Ni, with a correlation coefficient of 0.97. Other high positive correlations were found between Zn–Ni, Fe–Zn, As–Fe, As–Ni, Cu–Ni, and Fe–Mn.

The positive correlation between the elements reveal the common sources for the heavy metals in the soils of the study area. It can be attributed to the parent rocks as the concentrations in most of the samples do not exceed the background values of the Cataluña region. However, as it was described in the previous section, some samples present values that exceed the established background concentrations compared with the values in Table 6.7, which probably indicates an anomalous concentration. Figure 6.5 shows the scatterplots of the elements with high correlation coefficients.

![Scatterplot Cu-Ni](image1)

![Scatterplot Fe-Mn](image2)

![Scatterplot Cu-Zn](image3)

![Scatterplot Ni-Fe](image4)

Figure 6.5: Scatterplots of total concentrations of elements with the highest correlation coefficients.
6.4. Evaluation of the Results

Table 6.9: Correlation matrix for the extractable metals.

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.42</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>-0.10</td>
<td>0.21</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>0.88</td>
<td>0.36</td>
<td>0.15</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>0.40</td>
<td>0.94</td>
<td>0.34</td>
<td>0.51</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>-0.05</td>
<td>-0.68</td>
<td>-0.27</td>
<td>-0.07</td>
<td>-0.65</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>0.77</td>
<td>-0.12</td>
<td>-0.08</td>
<td>0.71</td>
<td>-0.12</td>
<td>0.22</td>
<td>1</td>
</tr>
</tbody>
</table>

The correlation coefficients for the extractable metals are shown in Table 6.9. The coefficients show that As, Cd and Ni present low to negative correlation with most of the analyzed elements. This can be interpreted as low affinity between these elements and the rest of the analyzed metals. However, elements like Fe–Mn, Cu–Zn, Cd–Cu and Cd–Zn present high correlation coefficients. This suggests that their concentrations in the soils are comparable and a high affinity exists between them. Figure 6.6 shows the scatterplots of the extractable elements that present the highest correlation among themselves.

![Scatterplot of Extractable Fe-Mn](image1)

![Scatterplot of Extractable Cu-Zn](image2)

Figure 6.6: Scatterplots of extractable concentrations of elements with the highest correlation coefficients.

The conditions for the Fe and Mn oxy-hydroxides to remain in solution are highly controlled by pH and Eh [39]. They must be strongly acid or strongly reducing. In the weathering environment, under oxidizing conditions, these compounds are normally found as precipitated forms. The Fe and Mn oxy-hydroxides play an important role as they may incorporate, by coprecipitation, other elements that normally are unaffected by pH and Eh. Another process of relevance attributed to these compounds is the adsorption, understood as the adhesion of ions or molecules to the surfaces of solid bodies with which they are in contact [39].

The maintenance of Cu, Zn, Pb, Ni, and As in the soils of the study area can be attributed to both processes explained above. The low concentration of extractable metals and the soil characteristics permit to conclude preliminary that the metals are in the soils forming precipitated compounds. The ability of Fe and Mn oxy-hydroxides to adsorb trace elements is known as the scavenging effect. This phenomenon has been
6.4. Evaluation of the Results

Table 6.10: Correlation coefficients between total and extractable metal concentrations for the analyzed metals.

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr. Coefficient</td>
<td>-0.48</td>
<td>0.94</td>
<td>0.41</td>
<td>-0.28</td>
<td>0.79</td>
<td>-0.59</td>
</tr>
</tbody>
</table>

Table 6.11: Correlation coefficients between total metals (upper portion), extractable metals (lower portion) and organic matter and clay fraction.

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Org. Matter</td>
<td>0.16</td>
<td>-0.39</td>
<td>-0.52</td>
<td>0.32</td>
<td>-0.14</td>
<td>-0.49</td>
<td>-0.72</td>
<td></td>
</tr>
<tr>
<td>Clay Fraction</td>
<td>-0.08</td>
<td>-0.36</td>
<td>-0.86</td>
<td>0.93</td>
<td>-0.44</td>
<td>-0.82</td>
<td>-0.74</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
<th>Fe</th>
<th>As</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Org. Matter</td>
<td>0.302</td>
<td>-0.491</td>
<td>0.457</td>
<td>0.612</td>
<td>-0.237</td>
<td>0.657</td>
<td>0.488</td>
<td></td>
</tr>
<tr>
<td>Clay Fraction</td>
<td>0.614</td>
<td>-0.562</td>
<td>-0.374</td>
<td>0.603</td>
<td>-0.556</td>
<td>0.528</td>
<td>0.889</td>
<td></td>
</tr>
</tbody>
</table>

studied and documented for authors like [39] and [35]. It has been interpreted as the main cause that control the fixation of heavy metals in soils. This fact could explain the maintenance of the metals in the soils of the Tabernas, where the elements that are most prompt to scavenge e.g., Cu and Zn, which are very mobile, present a high correlation.

Correlation coefficients were also calculated to establish a preliminary relationship between the concentrations of total and the respective EDTA-extractable forms among the six samples analyzed. From Table 6.10 it can be observed that a significant positive correlation exists between total and extractable Mn and total and extractable Fe can be observed. Then, an increase in the concentration total Mn and Fe will be associated with an increase in their extractable forms. In the case of Zn, the correlation factor of -0.28 indicates that a weak relationship between the total and extractable concentration. The total concentrations of Cu and As, present a negative correlation with their correspondent extractable forms and total and extractable Ni are positively correlated.

An attempt to establish the relationships that might exist between the total and extractable metal concentrations and soil properties, like clay fraction and organic matter content, was undertaken. For this, correlation coefficients were calculated for each metal and these properties and are shown in Table 6.11.

The total metal concentration and the clay fraction of the soils present a strong negative correlation for Ni, Fe and As. Then, high or low values of these metals are associated with low and high values in the clay fraction, respectively. For Pb, the significant positive correlation coefficient obtained, suggests a strong association between this element and the clay fraction in the soils. Apparently, there is no relationship between the clay content and Cu. A weak negative correlation exists for
Mn and Zn. This suggests that these minerals are likely to occur in the sandy fraction of the soils, which is the predominant according to the particle size analysis. This fraction has a low chemical activity; hence the mobility of these metals is quite restricted.

For the organic matter, the analysis of the data do not permit to establish a relationship with the concentration of the analyzed metals. Only a strong negative correlation can be inferred for this property and the content of As.

From the Table 6.11, a weak association between the extractable metals and the content of organic matter can be inferred, except for Zn, As. The highest correlation factor for extractable metals and clay content was obtained for Cd, indicating an important association between this metal and the clay fraction of the soil. The rest of coefficients don not permit to establish a clear relationship between the extractable metals and the content of clay in the soils.

The results of the particle size analysis showed that the soils of the Tabernas area present a sandy loam texture and low values of organic matter. These characteristics and considering the concentrations of the extractable fraction of the heavy metals, permit to suggest a low possibility for these elements to move and become available for the plants and groundwater system. Even though the tolerance values for the main crops in the study area, represented by olive and almond trees, as well as the values for the ground water according to its use are not available; the threat for this resources is low considering the factors described.

6.5 Soils and Human Activities

Anthropogenic heavy metal accumulation affects soils of industrialized regions. In addition to industrial pollution, agricultural contamination from non-point sources can contribute to heavy metal accumulation in soils. Therefore, it is known that in agricultural soils, the main sources of heavy metals are impurities and fertilizers, animal manures, pesticides, sewage and motor traffic fumes [12] and [65] in [48].

In the Tabernas area, industrial activities that pose a risk of soil contamination are not present. These type of activities are only restricted to small areas of sand and gravel quarrying and the production of energy from the solar plant. Among the activities described in the previous paragraph, the use of the soils for agricultural purposes would be the most important activity that might exert a negative contribution in the natural conditions of this resource in terms of pollution by heavy metal concentration.

The selection of the method and sampling sites were designed and carried out so that agricultural soils, either in use or abandoned were the target points to characterize them according to the physical and chemical properties described in Section 6.3.2.

According to the interpretation of the results obtained from the laboratory analysis discussed in Section 6.4, the concentrations of heavy metals in soils seem to indicate the existence of conditions that permit to infer a contamination by the accumulation of heavy metals. Instead, the results were explained as a natural process that concentrate the metals as precipitated forms or maintenance of metal governed by the adsorption of metals by oxy-hydroxides of Fe and Mn (scavenging effect). Ne-
6.6 Conclusions

Table 6.12: Associated land use class for analyzed samples. Concentration for total (T) and extractable (E) heavy metals in (ppm) and in (%) for total Fe.

<table>
<thead>
<tr>
<th>SAMPLE ID</th>
<th>Land Use</th>
<th>TCu</th>
<th>ECu</th>
<th>TMn</th>
<th>EMn</th>
<th>TNi</th>
<th>ENi</th>
<th>TPb</th>
<th>TZn</th>
<th>EZn</th>
<th>TFe</th>
<th>EFe</th>
<th>TAs</th>
<th>EAs</th>
</tr>
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<tr>
<td>JP01</td>
<td>Dry farming</td>
<td>16.3</td>
<td>247.7</td>
<td>25.1</td>
<td>33.5</td>
<td>40.4</td>
<td>2.1</td>
<td>3.9</td>
<td>16.1</td>
<td>19</td>
<td>7.6</td>
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<td>Protected and Hunting/Open space</td>
<td>24.1</td>
<td>439.5</td>
<td>24.9</td>
<td>43.4</td>
<td>47.7</td>
<td>2.98</td>
<td>3.7</td>
<td>19.5</td>
<td>28.3</td>
<td>7.5</td>
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<td>Irrigated tree, almond</td>
<td>26.1</td>
<td>203.4</td>
<td>33.5</td>
<td>21.3</td>
<td>47.7</td>
<td>4.01</td>
<td>1.24</td>
<td>14.8</td>
<td>18.8</td>
<td>9.1</td>
<td>3.0</td>
<td>1.0</td>
<td>0.9</td>
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<td>JP03b</td>
<td>Irrigated tree, almond</td>
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<td>183.9</td>
<td>22.3</td>
<td>19.9</td>
<td>34.6</td>
<td>4.44</td>
<td>1.35</td>
<td>12.3</td>
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<td>Irrigated tree, almond</td>
<td>26.2</td>
<td>245.5</td>
<td>22.2</td>
<td>30.7</td>
<td>47.1</td>
<td>2.73</td>
<td>1.69</td>
<td>12.2</td>
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<td>1.0</td>
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<td>JP05</td>
<td>Protected and Hunting/Open space</td>
<td>22.7</td>
<td>4.3</td>
<td>26.2</td>
<td>19.3</td>
<td>3.18</td>
<td>3.07</td>
<td>21.04</td>
<td>0.64</td>
<td>0.72</td>
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<tr>
<td>JP06</td>
<td>Protected and Hunting/Open space</td>
<td>19</td>
<td>327.8</td>
<td>26.8</td>
<td>38.3</td>
<td>51.8</td>
<td>3.06</td>
<td>0.93</td>
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<td></td>
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</tr>
<tr>
<td>JP07</td>
<td>Irrigated tree, almond</td>
<td>25.8</td>
<td>270.2</td>
<td>31.6</td>
<td>15.8</td>
<td>59.6</td>
<td>3.16</td>
<td>0.50</td>
<td></td>
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<td>300.8</td>
<td>43.1</td>
<td>10.3</td>
<td>82.8</td>
<td>3.98</td>
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<td>JP09</td>
<td>Dry farming</td>
<td>32.6</td>
<td>333</td>
<td>47.1</td>
<td>15.6</td>
<td>89.8</td>
<td>4.4</td>
<td>0.98</td>
<td></td>
<td></td>
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<td></td>
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<td>JP10</td>
<td>Irrigated tree, olive</td>
<td>40.7</td>
<td>373.8</td>
<td>40</td>
<td>23.4</td>
<td>68</td>
<td>3.59</td>
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<td></td>
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<td>JP11</td>
<td>Dry farming</td>
<td>38.5</td>
<td>107</td>
<td>463.7</td>
<td>52.9</td>
<td>25.8</td>
<td>52.2</td>
<td>2.98</td>
<td>4.64</td>
<td>10.5</td>
<td>0.69</td>
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<td>1.89</td>
<td>442.2</td>
<td>31.14</td>
<td>52.6</td>
<td>1.42</td>
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<td>98.3</td>
<td>0.72</td>
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<td>37.22</td>
<td>1.44</td>
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<td>52.5</td>
<td>473.9</td>
<td>49</td>
<td>150.1</td>
<td>86.5</td>
<td>4.75</td>
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<td>JP14</td>
<td>Dry farming</td>
<td>32.6</td>
<td>375.4</td>
<td>46.7</td>
<td>16.9</td>
<td>89.6</td>
<td>4.45</td>
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<td>JP15</td>
<td>Irrigated tree, olive</td>
<td>25.7</td>
<td>278.7</td>
<td>27.6</td>
<td>13.1</td>
<td>51.4</td>
<td>3.07</td>
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<tr>
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<td>Protected and Hunting/Open space</td>
<td>18.2</td>
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<td>166.8</td>
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<td>23.1</td>
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<td>28.3</td>
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<td>269.4</td>
<td>31.8</td>
<td>12.7</td>
<td>59.4</td>
<td>3.22</td>
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<td></td>
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<td>JP18</td>
<td>Mixed use</td>
<td>47.5</td>
<td>3.06</td>
<td>497</td>
<td>36.41</td>
<td>57.5</td>
<td>1.02</td>
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<td>4.92</td>
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<td>0.36</td>
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<td>JP19</td>
<td>Irrigated tree, almond</td>
<td>224.4</td>
<td>1.9</td>
<td>283</td>
<td>5.51</td>
<td>37</td>
<td>1.85</td>
<td>17.7</td>
<td>140.1</td>
<td>0.81</td>
<td>3.92</td>
<td>6.87</td>
<td>0.43</td>
<td>0.3</td>
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<tr>
<td>JP20</td>
<td>Mixed use</td>
<td>45</td>
<td>299.7</td>
<td>31.3</td>
<td>27</td>
<td>64.2</td>
<td>3.16</td>
<td>0.36</td>
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</tr>
</tbody>
</table>

vertheless, values that exceed the natural background concentrations in the areas where standard concentrations were available (Cataluña, The Netherlands, United Kingdom and Canada); were found in the Tabernas soils.

Table 6.12 presents the results of an overlay operation between the most recent land use map, that corresponds to the year 1995 and is shown in Figure 6.1, and the concentrations of heavy metals analyzed.

The land use associated with the nine samples identified in Section 6.4, with heavy metal concentrations that exceed the background values in the Cataluña Region; corresponds in 80% to agricultural activities like “Dry Farming”, “Irrigated Almond Trees” and “Mixed Use”. The samples located in parcels of “Dry Farming” present the highest values found in the study area. The sampling site JP19, which presents abnormal elevated concentrations of Cu and Zn, is located in a parcel where irrigated agriculture for almonds was the land use in 1995 and still was used for the same purpose at the moment of sample collection. Even though it was not established whether the agricultural activities, specially for the irrigated class, uses fertilizers, agrochemicals or pesticides to improve the soil conditions; this could be a factor that indicates certain “pressures” over the soil resource. This aspect as well as the establishment of background values for the study area should be considered to have a complete evaluation of these activities and their influence in the concentration of heavy metals.

6.6 Conclusions

- The results of the total and extractable concentrations of heavy metals in the soils of Tabernas seem to indicate that there is no evidence of soil pollution in the sampled area. However, in some points, values that exceed the background
concentrations established for the Cataluña Region, which is an environment relatively similar to the study area; were found. This may indicate the presence of anomalous values.

- The study of the heavy metals and other soil properties was based on a random sampling proposed as a first approach to preliminary evaluate the soil conditions. A wider and intensified sampling, concentrated in the points identified with high values and unsampled areas would permit to have a better understanding of the soil conditions and to establish the own background concentrations for the soils of the Tabernas area. These results should be used as the starting point of a monitoring program to evaluate the evolution and the relationship of the concentrations of heavy metals and the agricultural activities. The consideration of the climatic season and the different phases of these activities are aspects to consider.

- The positive correlation between the elements reveal the common sources for the heavy metals in the soils of the study area. It can be attributed to the parent rocks as the concentrations in most of the samples do not exceed the background values of the Cataluña Region.

- The soil characteristics derived from the analyzed properties like particle size and organic matter, permit to infer that the metals are found as precipitated compounds or as part of the structure of the minerals. Nevertheless, the scavenging effect of the Fe and Mn oxy-hydroxides can also play an important role in the maintenance of heavy metals in the soils of the study area.

- The results of the particle size analysis and organic carbon show that the soils of the Tabernas area present a sandy loam texture and low values of organic matter. These characteristics make the soils chemically low active, and considering the concentrations of the extractable fraction of the heavy metals, permit to suggest a low possibility for these elements to move and become available for the plants and groundwater system.
Chapter 7
Discussion and Evaluation of the Results

7.1 Introduction

The objective of this chapter is to evaluate the results obtained and synthesize the observations to propose two indicators that can be used in the study of land degradation. The influences of the natural environmental conditions as well as the human activities in the development of the morphodynamic processes and their implications in land degradation will also be discussed. The evaluation of the spatial distribution through time of the different processes will be used to infer tentatively “indicative trends”. All this information will permit to have a first approach to explain the natural and anthropogenic causes that contribute to the land degradation process in the Tabernas area. The advantages and limitations of the remotely sensed data used in this work as a support for the geomorphologic mapping will be discussed. Finally, the potentials and limitations of the study will be emphasized.

7.2 A First Approach to develop Indicators of Land Degradation in the Tabernas Study Area

The assessment of land degradation involves the study of multiple environmental components. The characterization of the state of the georesources (soil, water, geomorphology, climate, vegetation, etc.), geohazards (erosion, mass movements, flooding, drought, etc.) and the evaluation of human activities becomes a preliminary step to detect causes, extents, contributions and relationships that permit to evaluate the state and infer future trends in the land degradation process. Different methodologies have been proposed to evaluate land degradation. Such methods include the use of direct observations and measurements, mathematical modelling, remote sensing and environmental indicators [58].

The importance to characterize the state of the environment to develop policies for the sustainable management of the georesources is an issue that has been identi-
7.2. A First Approach to develop Indicators of Land Degradation in the Tabernas Study Area

fied globally in the last decades. In specific types of environments like the semi-arid Mediterranean Basin, land degradation has been affecting the landscape since historic times, [33]. To assess the degradation process, the construction and development of environmental indicators is a critical preliminary. The indicator will permit to answer the following questions:

- **What is happening in the environment?**
- **Why is it happening?**
- **What is the significance of the changes (natural and human–induced) and their implications for the future?**
- **How are we (scientist, decision makers, stakeholders, politicians, etc) responding to those changes?**

The term “geoindicator” was defined by the Commission on Geological Sciences for Environmental Planning, COGEOENVIRONMENT, of the International Union of Geological Sciences, IUGS, as “measures of surface or near-surface geological processes and phenomena that vary significantly over periods of less than 100 years and that provide information that is meaningful for environmental assessment” [7]. Similarly, [19], defines “geoenvironmental indicators” as a geological parameters that allows identification of changes in the environment that may be significant to the human race. That author distinguishes those geoindicators that can be selected with the purpose of environmental monitoring. The geoenvironmental indicators are applied to measure and monitor those processes in specific “geoenvironmental units” and a series of characteristics must be satisfied to achieve this purpose, such as, relevance, measurability, repeatability, comparability and frequency.

In Chapter 4 the different geomorphologic processes that affect the Tabernas study area were described. Also, their extent through three different (1956, 1981 and 1995) was evaluated by the multi-temporal interpretation of aerial photographs and satellite imagery. In Chapter 6 the concentration of heavy metals and other soil properties were evaluated to characterize the state of the soils. In this work, the consideration of the extent of the morphodynamic processes and the concentration of heavy metals are proposed as indicators contribute to the study of land degradation. The integration and aggregation of these indicators with other ones is to permit an overall assessment of the state of land degradation in the study area.

The indicators proposed in this study fulfil the characteristics to be considered as “geoenvironmental indicators”. They are relevant, in terms that they satisfy the objective to study a major problem of global, regional and local concern such as land degradation. They are measurable, by practical and analytical methods that are, relatively standard techniques (remote sensing, field data collection and laboratory analysis). These measurements can be repeated in different periods of time and they provide the basis to establish a monitoring program to continuously assess the changes in both indicators. The measurements are comparable and can be extrapolated to and from other areas with similar environmental conditions (e.g., background values for the concentration of heavy metals from the soils of Cataluña, can be tentatively
7.2. A First Approach to develop Indicators of Land Degradation in the Tabernas Study Area

compared with values from Tabernas). This permits to establish successive measure-
ments in time to obtain time-trends. The frequency between successive measure-
ments can be established according to local dynamic conditions.

The Tabernas study area was selected as one of the pilot study areas to carry
out the ELANEM project. The main objective of that project is to develop and test
a methodology to measure the environmental quality based on the identification, as-
essment and combination of a series of environmental indicators and indices. The
indicators proposed in this study are compatible with the objective of the ELANEM
project and can be used in a broad framework to assess and monitor land degradation
and its influences on environmental quality. The proposed indicators also fulfil the
characteristics that have been defined by the ELANEM working groups [47], [6], [58]
and [18] in [54]:

- Be objectively and scientifically measurable;
- Be preferentially quantitative;
- Be easy and cost–effective to measure;
- Be adapted to Mediterranean conditions;
- Be sensitive to environmental changes in project situation;
- Be simple in concept and accessible to both specialists and land managers;
- Be able to support policy decisions.

The possibility to measure geomorphologic processes with the use of remote sen-
sing and field observations constitutes an important achievement to understand
short-term changes in the natural environment. These changes can sometimes lead
to irreversible conditions, such as land degradation and desertification. The difficulty
to separate the influences of natural origin that cause the development of natural
processes from those that are induced by human activities, represents a challenge to
assess the environmental changes. The quantification of both influences is even a ma-
jor challenge for the earth scientists and specialists in related disciplines to provide
a complete assessment of the study areas.

7.2.1 Causes and effects in the development of the morphodynamic processes

The environmental situation in the year 1956 becomes the baseline to study the evo-
lution of the geomorphic processes and to establish the causes and effects that con-
tribute to its development. Past environmental conditions that could have had an
influence in the development of the indicators are not documented for the study area,
except for the mining activities that were active in the Sierra Alhamilla from 1890s
to 1942 [23]. The nature and extent of the previous changes that could have been
greater than those detected for the previous 50 years are also not available. They
could have exerted a major role in the development of morphodynamic processes and
they have not been established. This represents a major constraint in this study and
the assessed changes will be referred to the baseline condition described.

The factors that control the rate of geomorphic processes can be external and in-
ternal to the geomorphic system itself. Among the external factors, the climate has
a great relevance and also the human activities play an important role in fragile en-
vironments. Changes in the magnitude of the climatic variables (e.g., rainfall and
temperature) can lead to the modification in the rates of the geomorphic proces-
ses. They can even exert an influence in the internal factors (e.g., the nature of the
parent materials), [37]. Therefore, climatic changes can have a significant influence
on changes in morphodynamic processes and consequently in changes in the land-
forms.

For the study area, a long-term climatic dataset is not available. This represents
a limitation to infer relationships to establish the behaviour and the development
of the morphodynamic processes. The short climatic characterization presented in
Chapter 2 has established that the rainfall is concentrated in two periods (spring and
fall). This fact, despite the low values for the mean annual precipitation (248 mm)
represents an important parameter for the development of the erosive processes. The
presence of concentrated rainfalls in a short period of time can exceed thresholds
that may produce a rapid increase in the dynamics of the geomorphic processes. The
comparison of the distribution and the intensities of the rainfall at least during the
period of time considered for the analysis would permit to establish the described
relationships and have a better understanding of the morphodynamic in the study
area.

The results obtained in Chapter 4 show that the total area visibly affected by the
different morphodynamic processes has increased between 1956 and 1995 in 1.66%.
From 21.07% affected in 1956 to 22.73% in 1995 as shown in Table 7.1. The major
increase (1.3%) has occurred during the period 1956–1981. This coincides with the
period when major changes in the land use and land cover pattern were detected [2].
The situation for individual processes shows a relatively high increase in the period
1981–1995. It was interpreted as the evolution from one type of process to another
(e.g., the areas affected by “Moderate to High Sheet and Rill Erosion” evolve to areas
of “Gully and Sheet Erosion”). From that Table, it also can be observed how areas
affected by processes, such as, “Rill and Sheet Erosion”, “Gully Erosion” and “Gully
and Sheet Erosion” present a higher increment during the period 1981–1995.

In Chapter 5 the relationships between morphodynamic processes and natural
environmental components, as well as human activities were studied. They permit-
ted to establish that the geomorphologic processes are relatively more dependant on
natural components than on human activities, at least during the period of time con-
sidered for this analysis. The area affected by processes that coincide with areas
where changes in the land use and land cover patterns have occurred between 1956
and 1981 (the period with more dynamic changes) correspond to 7.19%, 5.26%, re-
spectively, (Tables 5.6 and 5.8).

The classes “Dry Farming” and “Seasonal Cultivation” present a close association
with the areas affected by sheet erosion. The preparation of the land for agricultural
activities involves the removal of the topsoil layer. Besides, during the field survey,
it was observed that soil conservation practices were not followed in some farms.
The crops were sowing in the sense of slope, not following the topographic contours,
favouring the development of erosive processes like sheet erosion.

It was demonstrated for specific places in the Sierra Alhamilla, the piedmont areas of the Sierra de Los Filabres and areas with hilly terrain developed from the sedimentary units, that a close association between the human activities and the development of morphodynamic processes exists, Figures 5.2, 5.6 and 5.11. The terrain, is exposed to the development of gully and sheet erosion as a consequence of the construction and development of new roads without the proper geotechnical management of the runoff water.

The close association between erosive processes, such as “Rill and Sheet Erosion”, “Gully Erosion” and “Gully and Sheet Erosion” and the geologic and geomorphologic units was established. The relatively high erodibility of the “Marls, Sandstones and Conglomerates”, (Thc11–12), and besides the described factor, the strong tectonic affection of the “Micaceous Schists and quartzites”, (PC–Pn), which correspond to the geomorphologic units “Badlands” and “Steep Relief of Sierra Alhamilla” and “Moderate Relief of Sierra de Los Filabres”, respectively; represents an important control of the lithologic and geomorphologic components in the development of the erosive morphologies.

To establish a generalized and absolute cause (natural or human) for the development and evolution of morphodynamic processes in the Tabernas area is difficult, especially when the area has been interfered with human activities since historic times. For the time span considered in this study, the environmental components and factors analyzed indicate a direct relationship between the natural conditions and the evolution of geomorphologic processes. Nevertheless, it was also demonstrated that the human influences also exerts certain control in this aspect. Then, the study of local conditions and the necessity to incorporate historic information as well as other environmental factors, e.g., climatic (long-term data sets and probably studies of paleoclimates), should permit to reconstruct past environmental conditions to establish the causes that govern the development of geomorphologic processes.

The increase in the extent of the area affected by morphodynamic processes represents a factor that contributes to the deterioration of the environmental and economic conditions. The damage and loss of natural vegetation that protects the topsoil is a factor that triggers the development of erosional processes. Then, the loss of soil that in some instance can be productive to support agricultural and other human activi-
ties starts. Moreover, the increase of the land affected by geomorphologic processes brings as a direct consequence the increase in the risk of land degradation that already affects the Tabernas study area.

The evolution of areas that presented surface erosion to areas affected by concentrated erosion, in the form of rills and gullies, represents an adverse effect in the study area. This results in an increment in the velocity and severity of the erosional processes. Consequently the degree of productivity decreases and a subsequent increase in the risk of degradation obtained.

Another negative factor that contributes to the development of the morphodynamic processes is the land abandonment. Ancient terraces systems that in the past were used for agricultural purposes were constructed at the foothills of the Sierras de Alhamilla and Los Filabres. The generalized industrialization processes in the 60s and 70s in the Mediterranean Region, generated the migration of rural population to industrialized cities and consequently the land abandonment of the agricultural practices developed in those terracing systems. The lack of soil conservation practices brought as a consequence the development of geomorphologic processes.

7.3 A Preliminary Analysis for the Indicators of Land Degradation in a Pressure–State–Response Framework

The ELANEM project partners have suggested an indicator based approach methodology [13], and a Pressure–State–Response, PSR, framework [45], [50], [61] to support the evaluation of the environmental quality in the different pilot areas. The results of this schema (indicator based approach and PSR) provide a useful and valuable indicator set to decision–makers and land managers [54]. The PSR framework, Figure 7.1, considers the indicators and their relationships between the pressures exerted on the environment by human activities, their ability to describe the state and changes of the environmental components, and the response of the society to the identified changes.

The PSR framework has been identified as a powerful approach to environmental assessment and state of the environment (SOE) reporting. In this study, the consideration of the relationships between natural components of the environment and human activities presented in Chapter 5 permits to integrate the results of an analysis of the indicators selected in a PSR framework. This will provide information that can contribute in the assessment of land degradation in the Tabernas area.

7.3.1 Extent of the area affected by morphodynamic processes in a PSR framework

In Chapter 5 and Section 7.2.1, the possible causes that determine the spatial distribution of the morphodynamic processes were discussed. It was determined that some areas affected by the geomorphic processes, specially the erosive ones, could be related to changes in the land use and land cover patterns between 1956 and 1981, Figu-
7.3. A Preliminary Analysis for the Indicators of Land Degradation in a Pressure–State–Response Framework

Figure 7.1: Pressure–State–Response framework, from (54).

7.3.2 Concentration of heavy metals in the soils in a PSR framework

The results of the total and extractable concentrations of the heavy metals analyzed seem to indicate that there is no evidence of soil pollution in the sampled area. However, there were samples with values that are slightly above the background, standard and threshold concentrations for elements like Cu, Ni, Pb and Zn. The land use associated with those samples corresponds in nearly 80% to agricultural activi-
ties (e.g., “Dry Farming”, “Irrigated Almond Trees” and “Mixed Use”). This conclusion is subjected to the limitations outlined in Chapter 6. The agricultural activities might indicate “pressures” over the soil resource by the incorporation of fertilizers, agrochemicals or pesticides, specially in the irrigated agriculture.

As a first attempt to evaluate the “state” of the soils in the Tabernas area, the concentrations of total and extractable metals, as well as other soil properties were measured. As indicated, these measurements permit to establish the soil conditions at the moment of sampling. The determination of the concentration values defines a baseline to compare the results with future measurements or to carefully establish the relationships with values obtained for areas of similar environmental conditions.

The definition of background, standard and threshold values permit to generate environmental policies of soil quality. These policies are designed to advocate a sustainable management of the soil resource. The environmental protection agencies or similar corporations, have the mandate to generate those policies as a “response” to the pressures identified and that could increase the risk of soil contamination as a consequence of human activities.

### 7.4 Is it Possible to Infer Future Trends in Land Degradation?

As a first approach to represent the evolution of the area affected by geomorphic processes, indicative trends will be tentatively presented. The results will indicate the extent of the area affected by morphodynamic processes in the year 2020. The spatial location of the new affected areas is not determined in the model applied.

The fact that only three years of record of the distribution of the morphodynamic processes were acquired, introduces limitations and uncertainties in the analysis and the results. Also, the statistical model to represent a tendency that predicts the extent of the selected processes carries its own degree of uncertainty because of the primitive knowledge of their behaviour through time.

To overcome the described limitations, the use of spatial prediction and modelling techniques would be the next step to consider. The established relationships between geomorphic processes and the geology, geomorphology and human activities could be used in these analyses and more confident results should be generated.

Future trends were calculated for the total area affected by geomorphic processes and for three individual processes that are representative among the different geologic and geomorphologic units. The data obtained from the affected areas calculated for the morphodynamic processes in the three years were transferred to a spreadsheet (M.S. EXCEL) and the trends were calculated using regression models (Figure 7.2). The values were plotted and the results of the best fit for a linear, logarithmic, polynomial, exponential and power regression models were compared.

Even though the natural processes do not always exhibit a linear behaviour, among the regression techniques applied, the results obtained with the linear regression model were considered to represent best the conditions of individual processes. The trends calculated with polynomial models showed a decrease in the area affected by the processes during the period between 1956 and 1981, which was not reflecting
7.4. Is it Possible to Infer Future Trends in Land Degradation?

Figure 7.2: Indicative trends for geomorphologic processes in the Tabernas study area

the morphologic conditions (according to the interpretations carried out to map the geomorphologic processes) and this situation was considered not representative.

The equations obtained from the tendency of behaviour for the geomorphic processes between 1956 and 1995 were used to calculate the extent of the area affected in the year 2020. The results are presented in Table 7.2. The rows “Total Area (Ha)” and “Total Area (%),” represent the extent of the area affected not only by the three morphodynamic processes selected for the evaluation of the future trends, but for all the processes considered in the analysis.

Table 7.2: Indicative trends for geomorphologic processes in the Tabernas study area.

<table>
<thead>
<tr>
<th>Processes/Year</th>
<th>1956</th>
<th>1981</th>
<th>1995</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (Ha)</td>
<td>Area (%)</td>
<td>Area (Ha)</td>
<td>Area (%)</td>
</tr>
<tr>
<td>Rill and Sheet Er.</td>
<td>1334.60</td>
<td>4.80</td>
<td>1421.72</td>
<td>5.12</td>
</tr>
<tr>
<td>Gully and Sheet Er.</td>
<td>26.20</td>
<td>0.09</td>
<td>54.08</td>
<td>0.19</td>
</tr>
<tr>
<td>Sheet Er. and Solution</td>
<td>282.00</td>
<td>1.02</td>
<td>286.40</td>
<td>1.03</td>
</tr>
<tr>
<td>Total Area (Ha)</td>
<td>5853.16</td>
<td>21.07</td>
<td>6214.76</td>
<td>22.37</td>
</tr>
<tr>
<td>Total Area (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 7.2 it can be observed that the tendency of the erosive processes in the next 18 years will continue gradually as it has been detected in the previous 50 years, if the natural conditions as well as human activities remain the same. The increase in the areas affected between 1956 and 2020 will correspond to 2.85% of the total area. According to the processes analyzed and the relationships established in Chapter 5, they will be developed in specific types of geologic units (e.g., the areas affected by
sheet erosion and solution would be likely to occur in limestone and gypsum rocks). The new areas resulting from rill and sheet erosion and gully and sheet erosion are likely to occur in the geomorphologic unit named “Badlands” or parts of the foothills of the Sierra de Los Filabres where these processes were detected between 1956 and 1995.

According to these trends, in the year 2020, one third of the study area will be affected by morphodynamic processes. The variability of the external factors that contribute to the development of the processes, e.g., climatic fluctuations, which can bring changes that will accelerate the rates of the erosive processes was not considered in this study. The effects of the human activities would be another factor to be incorporated in the analysis to obtained more realistic results. It was presented in Chapter 5 and also discussed in Section 7.2.1, that the effects that might be expected in the generation of geomorphologic processes from human activities would be at a local scale.

The evaluation of the trends suggest that a monitoring program to study the development of the erosive morphologies should be considered. Selected spots in geomorphologic units like the “Badlands” would permit the evaluation of the dynamics of these specific type of geomorphologic unit and its evolution according to the tendencies calculated.

The considerations that can be made regarding the distribution and concentration of heavy metals in the Tabernas soils in the future are limited. The fact that previous reference values are not available does not permit to predict indicative trends. Nevertheless, the importance of this study stems in the fact that the results can be used to set up a reference or baseline that should permit to establish comparisons with future analyses. This permits to suggest the usefulness to implement a monitoring program to study the evolution of the heavy metal concentrations in the soils.

The points that have to be considered to develop the monitoring program concern the expansion and intensification of the sampling with emphasis in those locations that present relatively high values in the concentration of heavy metals and unsampled areas. It should also be considered as a first step, the definition of background values for the study area to know what can be attributed to the natural concentrations of the parent materials and the contribution of external sources, like human activities. For this, the soil horizon “C” should be the target for the soil sampling. Generally this is the horizon where the metals originally in the parent rock are accumulated. The sampling should also consider the season when the different phases of the agricultural activities take place in the study area.

## 7.5 Potentials and Limitations of the Remotely Sensed Data to Support the Geomorphologic Mapping

The use of remotely sensed data to support the geomorphologic mapping in the Tabernas study area was presented in Chapter 3. Three different types of remotely sensed data were used: aerial photographs in analog and digital format, Landsat and ASTER imagery, both in digital format. A combined approach of visual and digital
image interpretation and classification supported by field observations was followed to complete the geomorphologic and morphodynamic process maps. For the Landsat imagery, enhancement techniques, like sum normalization, principal component analysis and colour composite generation were applied. The limitation of the ASTER dataset to only the VNIR bands was a constrain in the development of the study and a false colour composite was generated. A summary of the potentials and limitations of the remotely sensed data used in this study as a support for the geomorphologic mapping is presented in Table 3.1 and is further discussed below.

Terrain features related with broad physiographic units were best recognized by visual interpretation of the satellite imagery. The basement mountains were clearly separated from the sedimentary cover that corresponds to the hilly and low physiographic unit. The higher spatial resolution of ASTER data permitted to map medium scale (1:50,000) geomorphologic units as the ones defined in this study. Even though it was not used here, the possibility of stereoscopic vision in Band 3 is a major advantage that ASTER has when it is compared with Landsat and other sensors.

Regarding the identification of erosive morphologies, digital image interpretation, supported by previous visual interpretation and field data collection; permitted to recognize extensive areas affected by morphodynamic processes of natural origin and areas where human activities like agriculture contributes to their development. This is exemplified by the land cover category “Bare Soil for Agriculture”, well identified in the ASTER classified image. The spectral characterization of other land cover types related to those erosive morphologies, such as areas of bare soil and sparse vegetation has presented difficulties in this study. Low accuracy values were obtained for these specific classes.

The limitations that satellite imagery presents for geomorphologic mapping consists mainly in the identification of detailed or large scale geomorphic features, such as individual landforms (scarps, slopes), morphodynamic processes and a complete characterization of the drainage network.

The higher spatial resolution of the ortho-photo mosaic generated from the aerial photographs [2] permitted to recognize medium scale as well as detailed geomorphic features, such as geomorphologic units, individual landforms, extensive areas affected by the different morphodynamic processes, as well as individual processes (gullies, rills, solution). Stereoscopic vision and the higher spatial resolution allowed more precise definition of boundaries of geomorphologic units as well as the affected areas.

ASTER with its higher spatial resolution in the VNIR spectral range, stereo vision (in Band 3) and the generation of DEM offers more advantages than Landsat imagery. Also, the broad spectral resolution for the SWIR and TIR ASTER images, represents an important advance that permits to undertake a variety of applications in the earth and related sciences. The possibility to obtain ASTER datasets “free of charge” is other aspect that makes this sensor more attractive than Landsat (at present). Among the constraints that pose a limitation for ASTER is the restricted availability of geometrically and radiometrically corrected 1B products.
7.6 Potentials and Limitations of the Study

Different approaches, methods, techniques and sensors have been tested in the Tabernas study area to explore their potentials and limitations to propose the two indicators of land degradation.

7.7 Potentials of the study

- This study proposes two indicators that can contribute to the assessment of land degradation. The spatio-temporal characterization of the erosive morphologies and the determination of soil properties, represent a contribution in the knowledge and information to the study area. This information is useful to formulate policies for environmental and sustainable management of the natural resources. The policies would be related to define and implement measures to control the erosive processes and the definition of soil quality parameters.

- The possibility to detect changes in the geomorphologic processes using remotely sensed data and field observations, and the identification of the factors (natural and Human) that contribute to those changes, represents a first step to understand the complex dynamic environment and the land degradation in the study area.

- The results of this study establish a base line for the proposed indicators of land degradation. This base line constitutes the starting point to implement a monitoring program for each indicator. It will permit to continue building a spatio-temporal database that would be useful in future investigations. They would involve broad as well as narrow environmental aspects (e.g., completion of the set of indicators to evaluate land degradation and desertification and its influences on environmental quality in the ELANEM project, studies related to evolution of vegetation, effects of human activities on the environment).

- The integration of different spectral and spatial resolution remotely sensed data with field observations was an important aspect for the geomorphologic mapping in the study area. Medium and large scale geomorphologic elements were identified with satellite imagery and aerial photographs, respectively, and validated with field data collection that helped to improve the interpretability of the images. This aspect constitutes a significant advance to detect, map and suggest monitoring programs for natural environments under the influence of human activities.

- The possibility to obtain ASTER data “free of charge” and the process to generate interpretable products from raw and uncorrected data, represents an effort to incorporate products that are also suitable for other applications in the study area.
7.8 Limitations of the study

- The study of environmental issues such as land degradation requires a multidisciplinary approach that permits to combine and integrate the different aspects that involves this wide subject. In this study, two indicators of land degradation were proposed from a geomorphologic and soil perspectives. The necessity to incorporate indicators from other earth and related sciences (e.g., climatic, vegetation, soil and economics), is a relevant aspect to have a complete assessment of the land degradation and desertification processes that affects the Tabernas study area.

- The indicators proposed were defined with a limited number of samples. Three years of record to evaluate the extent of the area affected by morphodynamic processes and 21 soil samples to evaluate the concentration of heavy metals and other soil properties. This represents a constraint in the use of statistical methods to infer the indicative future trends for the geomorphologic processes and to assess the correlation and spatial distribution of the concentrations of heavy metals analyzed.

- The limitation of the ASTER data consists in the restriction of the analysis to the VNIR spectral range. The unavailability of geometrically and radiometrically corrected (1B) products did not permit to explore the capabilities of the rest of eleven bands in the SWIR and TIR spectral ranges to map land degradation features.
Chapter 8

Conclusions and Recommendations

8.1 Conclusions

- This study proposes two indicators that can contribute in the assessment of land degradation in the Tabernas study area: "the extent of morphodynamic processes" and "the concentration of heavy metals in the soils". Remotely sensed techniques supported by field observations, data collection, laboratory analysis and data integration in a GIS environment enabled the multi-temporal mapping of the morphodynamic processes and the determination of the actual state of the level of metal concentration in the soils. A first approach to analyze the indicators in a Pressure–State–Response was considered, and a baseline that corresponds to the year 1956 was established to evaluate future trends in the geomorphologic processes.

- The geologic setting of the Tabernas area strongly controls the landscape formation (morphostructural units), which influences the climatic conditions, the development of particular landforms and the associated morphodynamic processes. These factors represent a major influence in the vulnerability of the area to land degradation processes. Specific types of lithologic units, such as marls, sandstones and conglomerates are characterized by the formation of a badland type of landscape and are highly susceptible to the development of geomorphic processes such as rill, gully and sheet erosion.

- Different approaches, methods, techniques and sensors were tested to explore their potentials and limitations to map the erosive morphologies and the associated land cover to characterize land degradation features. A combined visual and digital image interpretation approach, supported by field observations permitted to accomplish this. The higher spatial resolution of the aerial photographs and the derived ortho-photo mosaics present a high potential to recognized individual morphodynamic processes and map the extent of the affected areas. The results obtained in the satellite image classifications presented low accuracy values for the land cover classes associated with erosive morphologies.
Factors such as individual band re-classification, where land cover classes present good spectral differentiation, and the use of other techniques, e.g., spectral unmixing; will permit to improve the classified images.

- The Tabernas area has been interfered by human activities since historic times. The information related to previous changes is not available. For the time span considered in this study, the analyzed factors point to a direct relationship between the natural components of the environment (geology and geomorphology) and the evolution of geomorphologic processes. It was also demonstrated that human influences, represented in changes in the land use and land cover patterns, and road construction and development also exerts certain control at a local scale in this aspect.

- The results of the total and extractable concentrations of heavy metals seem to indicate that there is no evidence of soil pollution in the sampled area. However, there were samples with values that slightly overcome background concentrations for elements like Cu, Ni, Pb and Zn; defined for the Cataluña Region in north-east Spain, which presents environmental conditions with certain similarities to the Tabernas area. The land use associated with those nine samples corresponds in nearly 80\% to agricultural activities e.g., “Dry Farming”, “Irrigated Almond Trees” and “Mixed Use”. This activities might indicate certain “pressures” over the soil resource by the incorporation of fertilizers, agrochemicals or pesticides, specially in the irrigated agriculture.

## 8.2 Recommendations

- Land degradation represents a topic of global environmental concern. The two indicators proposed only permit to have a first approach to explore the characteristics of this complex and wide subject in “recent times”, between 1956 and 1995. The construction, evaluation and aggregation of the proposed indicators with additional ones, defined from a perspective of the earth and related sciences, e.g., climatic and vegetation indicators; will permit to have a complete assessment of the ongoing land degradation in the Tabernas area. Integrated studies of Quaternary geology, landscape ecology and landscape sensitivity would permit to establish previous environmental conditions that can be used to establish an ancient baseline to study the evolution of the land degradation.

- The indicators proposed were defined with a limited number of samples. This represents a constraint in the use of statistical methods to infer the indicative future trends for the geomorphologic processes and to assess the correlation among the different metals analyzed. The necessity to incorporate new measurements to obtain data related to these indicators permits to propose the development of monitoring programs to study their evolution and adjust the indicative trends predicted. The sampling schema and periodicity should be defined based on the results of the random sampling applied in this study and the consideration of seasonal factors that control the agricultural production.
8.2. Recommendations

- The potentials and limitations of the ASTER sensor were not fully explored in this study due to it was not possible to correct the bands in the SWIR and TIR spectral ranges. New queries should be run in the ASTER website (http://asterweb.jpl.nasa.gov/default.htm) to obtained geometrically and radiometrically corrected products. This will permit to add new data to the spatio-temporal database for the study area and develop applications specially in the SWIR and TIR spectral regions to the study of land degradation.
References


References


References


Websites:
http://www.medalus.demon.co.uk/outline.html
http://www.frw.ruu.nl/fg/demon.html
http://www.citimac.unican.es/ELANEM/portada.html
http://asterweb.jpl.nasa.gov/default.htm
http://www.statlab.iastate.edu/soils/ssm/chap3ca.html
Appendix 1