Fluvial dynamics in Spain – Significance for palaeoenvironmental reconstructions and landscape evolution in the Western Mediterranean

DISSERTATION

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Abstract

The Western Mediterranean realm is considered as a region highly sensitive with regard to climate changes and landscape transformations. Within its semi-arid and semi-humid areas, even slight climatic changes but also human interventions may result in far-reaching consequences in respect of environment and ecological systems. Thus, research on landscape development has a high relevance in geosciences, especially in the light of current climate change research. It is a major concern to reveal regularities and patterns in past landscape evolution in order to provide a basis for the assessment of future developments. For the reconstruction of late Quaternary environmental conditions fluvial sediments play an important role as they almost uniquely reflect landscapes and landscape changes on a regional scale. This is due to the fact that fluvial dynamics and all enclosed processes are based on multi-causal relationships and a variety of factors like climatic conditions, vegetation development, human impact, or tectonic activity finds expression in fluvial dynamics.

About 70% of the Iberian Peninsula is influenced by moist Atlantic air masses, but in the whole area there is a considerable research gap concerning the exploration of fluvial archives. Taking this into account, this dissertation aims to systematically work out fluvial sediment successions of two river systems, namely the Jarama River in central Spain and the Guadalete River in southwestern Spain. For complementary considerations, first stratigraphic results from the middle to lower Guadalquivir River in southern Spain will be consulted. In a first step, the objective is to intensively study and document sediment profiles for the purpose of deriving a valuable composite profile for each river system. In a second step, the significance of these composite profiles regarding palaeoenvironmental conditions as well as changes will be examined. Beside the reaction of fluvial systems towards climatic changes, relationships with other influencing factors are a main issue. On the basis of a supra-regional comparison a possible coupling of fluvial geomorphic systems and large-scale climate fluctuations shall be analyzed. Furthermore, it is intended to address issues like system connectivity or varying response times and response durations.

The bases for these considerations are abundant sedimentary profile records supported by electrical resistivity tomography and percussion drillings. Stratigraphic work includes the differentiation of sediment units, the identification of soil horizons, and the correlation of specific layers and horizons across different profile sections based on sedimentologic and pedogenetic characteristics. Subsequent soil-chemical and sedimentological laboratory analyses on certain key-profiles imply grain-size analyses, the measurement of organic carbon content, calcium carbonate content, pedogenic and total iron contents, as well as magnetic susceptibility. Laboratory analyses are used to strengthen results of field work and to differentiate between soils and soil sediments in ambiguous cases. The chronological resolution of the sediment successions will be provided by radiocarbon dating. The final aim is to work out a detailed fluvial sedimentation history for the late Quaternary. The precise characterization of the
catchment areas, together with a comparison of the stratigraphic findings and secondary archive information from the literature, will enable the identification of relationships between fluvial dynamics and different influencing factors.

In this dissertation, 36 profile sections have been worked out intensively. Furthermore, 13 percussion drillings were conducted in floodplain positions with insufficient exposure conditions. For the chronological frame 70 radiocarbon samples have been dated. The obtained results show a significant pattern of sedimentation periods and phases of stability associated with soil formation for each river system. The sedimentation history of the Guadalete and Guadalquivir Rivers could be reconstructed for the last 15 ka, while conclusions with regard to sedimentation dynamics of the Jarama River could be drawn for a period of 43 ka. Thanks to an abundance of available studies on other terrestrial archives with climatic or environmental relevance, it was possible to assess the influence of different parameters such as climate, vegetation, humankind, tectonics, and base-level changes on fluvial sedimentation dynamics. It emerged that, first and foremost, rapid climate changes had significant impact on the mobilization of sediments in the catchment area as well as their deposition in floodplain positions. On the other hand prolonged periods of climatic amelioration caused floodplain stability along with soil formation, as documented for the time spans between 13.3 and 12.7 ka, 7 and 5.1 ka, 2.8 and 2.3 ka, 1.4 and 1.2 ka, as well as 0.8 and 0.5 ka cal. BP in several river systems. Periods of increased sedimentation were initiated by phases of climatic aridification that affected fluvial systems through the weakening of the vegetation cover and the accentuation of the hydrological discharge regime. Corresponding patterns have been found for the time intervals between 8 and 7 ka, 5 and 3.8 ka, 2.2 and 1.5 ka, as well as around 1 ka and 0.4 ka cal. BP. The supra-regional effectiveness of the factor climate is contrasted by a strong regional individuality of the river catchments that is expressed by further, regionally limited phases of fluvial activity. Crucial to this development – apart from regional climate differences – are, inter alia, tectonic movements as evidenced for the Jarama River system in central Spain, or late Pleistocene and Holocene sea-level fluctuations that primarily affected fluvial dynamics along the lower course of the Guadalete River in southwestern Spain. Furthermore, it can be shown that variations in time and duration of fluvial system response are attributable to differing buffer capacities of river catchments towards external influences. The increase of human impact during the late Holocene apparently provoked a reinforcement of the effects of climatic impulses. There are clear evidences for the participation of humans in the mobilization of sediments; however, concerning the degree of influence it is hardly possible to differentiate between the factors humans and climate.
Kurzfassung


Grundlage für diese Betrachtungen bilden dabei aus zahlreichen Geländeaufnahmen resultierende Profilaufnahmen, sowie Ergebnisse geoelektrischer Messungen und Bohrsondierungen. Stratigraphische Arbeiten belaufen sich zunächst auf die Untergliederung verschiedener Sedimenteinheiten, die Ausweisung von Bodenhorizonten, sowie die Korrelation einzelner Schichten und Horizonte über unterschiedliche Profile hinweg anhand charakteristischer sedimentologischer und pedogenetischer Merkmale. Nachfolgende bodenchemische und sedimentologische

Table of contents

Acknowledgements ........................................................................................................................................ III
Abstract ......................................................................................................................................................... IV
Kurzfassung .................................................................................................................................................... VI
Table of contents ......................................................................................................................................... IX
List of figures .................................................................................................................................................. XIII
List of tables .................................................................................................................................................. XV
List of abbreviations ................................................................................................................................... XV

1 Introduction .................................................................................................................................................. 1

1.1 Relevance of fluvial records in the context of climate change and landscape evolution in the Western Mediterranean .......................................................................................... 1

1.2 Environmental significance of fluvial deposits ...................................................................................... 4

1.3 Objectives and methodological approach .............................................................................................. 6

2 Late Quaternary fluvial dynamics of the Jarama River .............................................................................. 11

2.1 Introduction ............................................................................................................................................. 13

2.2 Study area ................................................................................................................................................ 14

2.2.1 Geological and tectonic background .................................................................................................. 15

2.2.2 Geomorphological setting of the Jarama valley .................................................................................. 16

2.3 Methods .................................................................................................................................................. 16

2.4 Fluvial architecture and characteristics of the sedimentary units ....................................................... 18

2.4.1 Sequence 1 – Late Pleistocene ........................................................................................................... 18

2.4.2 Sequence 2 – Early to Mid-Holocene ............................................................................................... 22

2.4.3 Sequence 3 – Mid-Holocene to Roman period .................................................................................. 25

2.4.4 Sequence 4 – Little Ice Age ............................................................................................................. 27

2.5 Interpretation - Stages of floodplain development ............................................................................... 29

2.5.1 Extensive aggradations during Marine Isotope Stage (MIS) 3 ....................................................... 29

2.5.2 Increased fluvial activity in the course of the Last Glacial Maximum (LGM) .................................. 32

2.5.3 Sand deposits (Unit 3) at the end of MIS 2 ...................................................................................... 33

2.5.4 Younger Dryas and Early to Mid-Holocene sedimentation .............................................................. 36

2.5.5 Mid-Holocene warm period and climatic collapse .......................................................................... 37

2.5.6 Highly dynamic floodplain aggradations and 3.0 ka-aridity crisis ................................................. 38
2.5.7 Extensive sand deposition at 2.8 ka BP and following floodplain stability ................................................................. 40
2.5.8 Flood loam accumulation during the Roman epoch ................. 41
2.5.9 Alternating flood loam accumulation and soil formation during the Medieval period ................................................................. 42
2.5.10 Accentuated fluvial dynamics during the Little Ice Age and recent flooding ............................................................................. 43
2.6 Human influence versus climatic control factors .......................... 43
2.7 Significance of fluvial records in a spatial context ............................ 45
2.8 Conclusion .................................................................................. 46

3 Late Pleistocene and Holocene fluvial dynamics of the lower Guadalete River ................................................................. 58
3.1 Introduction .................................................................................. 59
3.2 Study area ................................................................................... 60
3.3 Methods ....................................................................................... 63
3.4 Stratigraphic findings and sedimentation patterns within the Guadalete valley ....................................................................... 66
3.4.1 Upper downstream section ........................................................ 66
3.4.1.1 Late Pleistocene sediments ....................................................... 66
3.4.1.2 Mid-Holocene sediments (5000 - 2000 cal. a BP) ..................... 68
3.4.1.3 Late Holocene sediments (<2000 cal. a BP) .............................. 74
3.4.1.4 Composite profile ..................................................................... 76
3.4.2 Lower downstream section close to the estuary ......................... 78
3.4.2.1 Early Holocene sediments (~10000 - 8000 cal. a BP) ................ 78
3.4.2.2 Mid- to late-Holocene sediments (<8000 cal. a BP) ................. 80
3.5 Interpretation – Floodplain evolution and the influencing factors .... 82
3.5.1 Stages of floodplain evolution ..................................................... 82
3.5.1.1 Late Pleistocene dynamics (SU-1 to SU-3) ................................. 82
3.5.1.2 Early Holocene dynamics (SU-4 to SU-7) .................................. 84
3.5.1.3 Mid-Holocene dynamics (SU-8) .............................................. 86
3.5.1.4 Mid-Holocene aridity collapse (SU-9a to SU-9c) ...................... 87
3.5.1.5 Late Holocene dynamics (SU-10 to SU-12) .............................. 88
3.5.1.6 Increased dynamics during the Little Ice Age (LIA) (SU-13a to SU-14) ... 90
3.6 Conclusion ................................................................................... 91

4 Western Mediterranean environmental changes ............................. 104
4.1 Introduction .................................................................................. 106
4.2 Study area ................................................................................... 107
# Table of contents

4.2.1 Jarama River ................................................................................. 109  
4.2.2 Guadalete River ........................................................................... 110  
4.2.3 Guadalquivir River ....................................................................... 110  

4.3 Methods .............................................................................................. 111  

4.4 Results .................................................................................................. 113  
4.4.1 Stratigraphic findings of the Jarama River ..................................... 113  
4.4.1.1 Fluvial architecture .................................................................. 113  
4.4.1.2 Sedimentation patterns ......................................................... 115  
4.4.1.3 Periods of soil formation ....................................................... 117  
4.4.2 Stratigraphic findings of the Guadalete River ............................... 118  
4.4.2.1 Fluvial architecture .................................................................. 118  
4.4.2.2 Sedimentation patterns ......................................................... 120  
4.4.2.3 Periods of soil formation ....................................................... 122  
4.4.3 Stratigraphic findings of the Guadalquivir River ......................... 123  
4.4.3.1 Fluvial architecture .................................................................. 123  
4.4.3.2 Sedimentation patterns ......................................................... 124  
4.4.3.3 Periods of soil formation ....................................................... 126  

4.5 Discussion ............................................................................................ 127  
4.5.1 General view of fluvial architectural patterns as basis for interpretations .................................................................................. 127  
4.5.2 Fluvial dynamic patterns and possible forcing mechanisms .......... 127  
4.5.3 The role of climate in triggering fluvial dynamics ......................... 131  
4.5.4 Supra regional comparison of examined floodplain records .......... 132  
4.5.5 Variability of fluvial dynamics: A matter of sensitivity? .............. 134  
4.5.6 Large-scale consideration of Western Mediterranean fluvial records .................................................................................. 136  
4.5.7 Interrelations between North Atlantic sea surface temperature and landscape dynamics on the Iberian Peninsula ......................... 138  
4.5.8 Landscape dynamics and corresponding atmospheric conditions .. 138  

4.6 Conclusion ............................................................................................ 139  

Acknowledgements .................................................................................. 141  
References ................................................................................................. 141  

5 Synthesis ................................................................................................. 153  
5.1 General architectural patterns of examined river floodplains in Spain ... 153  
5.2 Assessment of influencing factors and their relevance for fluvial dynamics .................................................................................. 154  
5.3 Interpretations in terms of palaeo-environmental conditions .......... 157  
5.4 Comparative consideration of the various study areas .................... 158  

XI
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>Climate change and implications for fluvial system behavior</td>
<td>159</td>
</tr>
<tr>
<td>5.6</td>
<td>Outlook</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>162</td>
</tr>
</tbody>
</table>
List of figures

Figure 1.1. Flowchart of the work plan that was implemented during the research process ................................................................. 9
Figure 2.1. Location of the study area in central Spain ............................................ 15
Figure 2.2. Sedimentary sequences and sediment units of the profiles
   Holcim and Holcim-2 ............................................................................. 19
Figure 2.3. Profile sections perpendicular to the Jarama river course ................... 21
Figure 2.4. Sedimentary sequence and sediment units of the Aranjuez profile . 23
Figure 2.5. Sedimentary sequences and sediment units of the profiles
   Titulcia, Seseña and San Martin .............................................................. 24
Figure 2.6. Species composition of water-logged samples and charcoals ......... 26
Figure 2.7. Sedimentary sequence and sediment units of the Peralta profile .... 28
Figure 2.8. Profile section of the Peralta profile ......................................................... 28
Figure 2.9. Schematic sketch of the evolutionary development of the Jarama
   River floodplain ......................................................................................... 30
Figure 2.10. Summary of the late Quaternary fluvial sedimentation history ...... 34
Figure 3.1. Location of the Guadalete River catchment in western Andalucía ... 61
Figure 3.2. Detailed map of the study area.............................................................. 62
Figure 3.3. Late Pleistocene succession of the profile section "Pozo Romano" .. 67
Figure 3.4. Mid- to late Holocene succession of the profile "Braza-II" ............... 69
Figure 3.5. Identified tree species in absolute numbers of samples .......... 70
Figure 3.6. Compilation of profile sections ............................................................. 71
Figure 3.7. Elevation profile of the cross-section "Junta de los Rios" and results
   of ERT-measurements ........................................................................... 72
Figure 3.8. Profile section "Rancho Romero-I" ...................................................... 73
Figure 3.9. Sediment successions and analytical data ............................................ 75
Figure 3.10. Composite profile of the upper and lower downstream sections.... 77
List of figures

Figure 3.11. Profile descriptions and analytical data of drillings along the La Ina-section ................................................................. 79
Figure 3.12. Profile descriptions and analytical data of drillings along the Medina-section .............................................................. 80
Figure 3.13. Compilation of cross-sections taken from a digital terrain model .... 83
Figure 3.14. Compilation of Late Pleistocene and Holocene periods of sedimentation, incision and floodplain stability ..................... 85
Figure 4.1. Location of the three studied river catchments in Spain............. 108
Figure 4.2. Schematic sketch of the lower Jarama River floodplain architecture .................................................................................. 114
Figure 4.3. Selected key profiles from the Jarama River system .................. 116
Figure 4.4. Composite profiles of Guadalete River floodplain .................... 119
Figure 4.5. Selected key profiles from the Guadalete River system ............. 121
Figure 4.6. Profile section `Posadas` ........................................................ 124
Figure 4.7. Profile section `Alcolea` .......................................................... 125
Figure 4.8. Summary of late Pleistocene and Holocene Jarama River floodplain dynamics .............................................................. 129
Figure 4.9. Summary of late Pleistocene and Holocene Guadalete River floodplain dynamics ............................................................. 130
Figure 4.10. Summary of late Pleistocene and Holocene floodplain dynamics in three studied Atlantic river basins .......................... 133
Figure 4.11. Conceptual model of nonlinear fluvial response to climate forcing ............................................................................... 136
Figure 4.12. Compilation of palaeo-flood information ............................... 138
Figure 5.1. Schematic sketch of the lower Jarama Valley between 5 and 4 ka cal. BP ................................................................. 156
List of tables

Table 2.1  Radiocarbon dates obtained on late Pleistocene and Holocene sediment sequences of the Jarama River ........................................... 17
Table 3.1  Radiocarbon dates from the Lower Guadalete River sediments ....... 65
Table 4.1  Radiocarbon dates obtained from Jarama, Guadalete and Guadalquivir River systems .............................................................................. 112
Table 4.2  Characterization and estimated exposure duration of late Pleistocene and Holocene floodplain soils in the Jarama River floodplain ........................................................................................................ 118
Table 4.3  Characterization and estimated exposure duration of late Pleistocene and Holocene floodplain soils in the Guadalete River floodplain ........................................................................................................ 123

List of abbreviations

A.s.l.  Above Sea Level
Cal BP  Calibrated Before Present
ERT  Electrical Resistivity Tomography
LGM  Last Glacial Maximum
MIS  Marine Isotope Stage
NAO  North Atlantic Oscillation
SST  Sea Surface Temperature
SU  Sediment Unit
1 Introduction

1.1 Relevance of fluvial records in the context of climate change and landscape evolution in the Western Mediterranean

The Western Mediterranean realm is an area highly sensitive to climate changes characterized by the prevalence of semi-arid to semi-humid climate conditions (Lautensach 1964) and an accentuated interannual variability with a high contribution of extreme precipitation events (Toreti et al. 2010). It is even considered as one of the world’s hotspots of climate change (Giorgi 2006) especially vulnerable to future global change. A review of climate change projections by Giorgi & Lionello (2008) revealed a severe drying and warming of the Mediterranean region during the present century with precipitation decrease of more than 25% and warming exceeding 4-5°C (see also Bangash et al. 2013). Impending effects like the increasing occurrence of extreme events such as droughts or floods may have increasingly devastating effects on natural ecosystems.

Related to these projections, climate change adaption will be a challenging issue for societies that populate affected regions. However, in addition to direct effects of climate changes on hydrological systems, the biological environment (especially vegetation) as well as geomorphologic systems will experience significant changes. Such modifications may initiate serious alterations of landscapes. In particular landscapes that already underwent dramatic changes due to human activity that created an imbalance of ecological process structures appear exceptionally fragile and susceptible to further external forcing (e.g. Jalut et al. 2009, Fletcher et al. 2013, Wanders and Wada 2014). In certain cases only minor environmental oscillations are necessary to initiate the devestation of eco-systems as it turns out in a number of examples of active badland formation from the Mediterranean (Torri et al. 2000). But even less drastic effects may compromise human communities. Negative consequences involved in an above-mentioned landscape development may include the debasement or even loss of farmland, or hazards related to extreme events such as heavy precipitation and floods that may directly endanger settlement areas and economic assets e.g. in floodplains, or the increase of frequency, duration and intensity of droughts and heat waves, which represents a direct risk to the public and the environment including water resources, vegetation dynamics and agriculture (Xoplaki et al. 2012).

However, when dealing with climate change impacts it is crucial to assess specific reactions of landscapes on climate forcing. A promising approach to estimate current and future developments is to examine reaction patterns of climate fluctuations in the past (Luterbacher et al. 2012). The question arises whether and how the evolution of landscapes can be reconstructed. For this purpose three main variables have to be considered. (I) Climate system: Climate is probably the major factor that influences
landscape evolution within a late Pleistocene/Holocene timeframe and a number of terrestrial archives provide climate relevant data for the period concerned (e.g. Luterbacher et al. 2012, Fletcher and Zielhofer 2013, Moreno et al. 2014).

(II) Vegetation dynamics: Vegetation reacts directly to climate fluctuations and is of major relevance to sediment dynamics on the earth’s surface (Carrión et al. 2010, López-Merino et al. 2012, and Feurdean et al. 2014). Therefore, vegetation dynamics are reflective for the fragility inherent in specific landscape units. As an aggravating circumstance, after a certain point of time in the Holocene the natural vegetation development was superimposed (or complemented) by an anthropogenic impact and thus, it is a challenge to separate the changing influence of climate and humans on the environment (e.g. Faust et al. 2004, Carrión et al. 2007, 2010). (III) Geomorphologic systems: Archives that reflect dynamics of geomorphologic systems are essential for unraveling morphogenesis in the context of landscape evolution. Dependant on scale and scope, morphodynamics may combine the effects of climate and vegetation systems (e.g. Marston 2010, Nadal-Romero et al. 2015). Once process parameters are identified, geomorphologic archives provide the opportunity to assess the changing impact of different parameters with time (Eybergen and Imeson 1989), to define periods of morphogenetic activity and stability (Harvey 2007), or furthermore to estimate the strength of processes involved (Faust and Schmidt 2009, Dusar et al. 2012).

Dealing with landscape evolution, fluvial dynamics occupy a special role among geomorphologic systems. First of all, fluvial dynamics are an expression of a wide variety of processes that take place within a river catchment. In contrast to systems that operate in small catchments like slope systems that are very susceptible to local perturbations such as wild fires or human activity, fluvial dynamics generally reflect the development of larger areas. They are thus less sensitive to local perturbations but still sensitive to developments that are representative of larger parts of the catchment area. Related to this, catchment size is an important issue when dealing with questions like system reaction, response times or sediment yield within the catchment in general (de Vente and Poesen 2005, Slaymaker 2006, Hoffmann et al. 2010, Vanmaercke et al. 2011).

Concerning the relevance of fluvial records, catchment erosion caused by a weakening of the environment may be mirrored, just as ecological stability accompanied by continuous vegetation cover (Faust et al. 2000, Lespez et al. 2011). Fluvial records may be well suited for the reconstruction of periods of floodplain activity and stability that in turn may allow conclusions about the development of a landscape over time.

There are several examples which illustrate that fluvial systems are sensitive to climate fluctuations and that fluvial records are a useful tool for palaeoenvironmental reconstruction, such as Faust et al. (2000), Schulte (2002), Benito et al. (2003), Thorndycraft and Benito (2006), Benito et al. (2008), Sancho et al. (2008), Schulte et al. (2008), Uribellarea and Benito (2008), Vis et al. (2008), Ortega and Garzón (2009), Bullón (2011), Houben et al. (2011) and Gómez-Paccard et al. (2013) for the Iberian
1 Introduction

Peninsula or Wengler and Vernet (1992), Faust et al. (2004), Zielhofer et al. (2008), Linstädter and Zielhofer (2010) and Zielhofer et al. (2010) for the Mediterranean Maghreb. Generally, these studies are based on the examination of floodplain sediments and slack water deposits and provide different time series depending on the potential of the respective archives. However, apart from some isolated findings, conclusive information that arise from reliable floodplain stratigraphies that cover such a long time period as the Late Pleistocene and the Holocene are rare for Atlantic river basins in Spain. These river basins cover an area of more than two thirds of Spain and information concerning climate changes and the response of landscape systems is of broad interest, not only for scientific aims.

This dissertation aspires to investigate fluvial dynamics and the interplay with climate and vegetation systems in three different river basins within the Atlantic influenced part of Spain. In these basins the striking characteristic related to climate conditions is the passage of cyclones that carry moist air masses from the Atlantic. This is a result of westerly winds that are actually driven by the North Atlantic Oscillation (NAO; see Rodrigo et al. 2000, Muñoz-Díaz and Rodrigo 2003, Trigo et al. 2004) leading to the typical winter rain climate with most of the precipitation falling between autumn and spring. Currently, atmospheric circulation patterns linked to the NAO are considered as being mainly responsible for the intensity and temporal distribution of precipitation (Trouet 2009), which in turn may be a determining influencing factor for the fragility of landscapes and fluvial dynamics. Exploring the nature of interrelations between rainfall regime and catchment dynamics in the past is likewise an objective of this research.

The examined river basins are located alongside a gradient of annual precipitation values that leads from semi-humid Southwestern Spain to semi-arid Central Spain. These study areas are:

(1) Guadalete River, Western Andalucía. With an extent of around 3400 km² the Guadalete River has a medium-sized catchment area. Rainfall varies between 646 mm year⁻¹ in the lowlands nearby Jerez de la Frontera and more than 2000 mm year⁻¹ in the Sierra de Grazalema.

(2) Jarama River, Region Madrid and Northern Castilla-La Mancha. The catchment area has a size of 11,500 km² and rainfall varies between 456 mm year⁻¹ within the central Madrid Basin and up to 1400 mm year⁻¹ in the Sierra de Guadarrama.

(3) Guadalquivir River, Andalucía. The catchment points to an extent of ~57,000 km² with rainfall varying between 400 and 1400 mm year⁻¹. (As solely piecemeal results were obtained, no conclusive evaluation of this study area was implemented.)

For more detailed information for each study area see chapters 2.2, 3.2 and 4.2.
1.2 Environmental significance of fluvial deposits

In each river floodplain, different types of fluvial sediments are arranged in a certain spatial pattern through the effect of fluvial sedimentation and erosion processes, which leads to the development of a specific fluvial architecture. Every sedimentary unit taken as architectural element bears a specific indication concerning the sedimentary environment, which allows deducing the 'fluvial style' (Miall 1985) e.g. including runoff patterns and channel patterns, and the position related to the active river channel during the time of sedimentation. If additionally the age of sedimentary layers and the character of interposed floodplain soils are taken into account, duration and intensity of sedimentation processes as well as duration of floodplain stability may be estimated. But likewise the erosion of sediments reflected by discordances or the decoupling of floodplain levels from active river dynamics (terrace formation) provides information about runoff patterns, load capacity ('Lane's balance' in Lane 1955) or even changes of the base level of erosion (Collinson 1996). Limitations to interpret stratigraphic findings are e.g. reported by Schumm (1991) or Blum and Törnqvist (2000).

In principle, according to the classification shown in Collinson (1996) the river systems examined in this research can be classified as coarse-grained bed load rivers that carry gravels and sands and likewise large amounts of suspended load. Here, three different sedimentary environments can be divided after Reineck (1980), namely channel deposition, bank deposition and flood basin deposition. Following compilation gives a rough overview of possible description and interpretation of different fluvial deposits on the basis of grain-sizes.

1. Conglomeratic gravelly deposits are reflective for high-energy bed load streams; gravel units may show lateral accretion surfaces with epsilon cross-bedding pointing to channel movement and point-bar development or may be structureless with longitudinal bars consisting of lenticular trough shaped elements due to braiding channel patterns (Ori 1982, Bridge 1993, Collinson 1996).

2. Sand bodies may occur in form of channel deposits with small isolated units or large sheets related to point bars of meandering rivers as well as bars in braided systems (Allen 1963, Collinson 1996); in absence of gravel deposits extensive sand bodies may be indicative for temporal reduction of flow energy. Furthermore, sands may occur as levee or in floodplain positions e.g. related to crevasse splays and chute channels or temporary tributary channel formation during high flood events (Reineck 1980, Miall 1985). Laminated sand sheets even in distal floodplain positions may be indicative for flash flood events, while fining-upward sequences are representative for waning flood conditions (Miall 1985).

3. Overbank fines (floodplain deposits) generally consist of cohesive flood loams (fine sand, silt and clay) and result from vertical aggradations of suspended
sediments during flooding events (Miall 1985, Collinson 1996, Zielhofer et al. 2004). Clayey sediments may be deposited in most distal floodplain positions but also in secondary floodplain channels in form of waning flood deposits (partly also in abandoned channels of the main channel belt).

Generally, erosion, transport and deposition of specific grain-sizes depend on the balance between the strengths of the flow (velocity) and the size and density of sediment particles (see Hjulstrom curve, e.g. in Reineck 1980). Thus, transported grain-sizes usually decrease with increasing distance to main channels.

Apart from information about stream-power deducible from mean grain-sizes, the spatial arrangement and the inner structure of sediments are important sources of further information. The allocation of fluvial facies to certain architectural elements as shown by Miall (1985) is a basic requirement to establish a link to channel patterns and runoff properties. There is a substantial literature about the classification of fluvial depositional styles based on the combination of different architectural elements (e.g. Miall 1985, Richards 1986, Nanson and Croke 1992 and Bridge 1993, Charlton 2007).

In order to provide a genetic classification of floodplains, e.g. Nanson and Croke (1992) relate the evolution of floodplains to stream power and sediment character. First, they define three main processes of floodplain formation: (1) Lateral point-bar accretion on convex banks of meandering river systems with migrating river channel. (2) Overbank vertical-accretion due to overbank deposition during flood events with the formation of Levees, crevasse splays and back swamp deposits. (3) Braid-channel accretion characterized by intense channel shifting, local aggradations and later channel incision, and the formation of extensive bars. These processes, together with three less common processes produce singly or in combination a variety of floodplain types. These again may be classified according to different energy environments and cohesiveness of sediments.

Resulting from such classification approaches, it should be possible to deduce sedimentary environments from the presence of a certain constellation of architectural elements (or facies association in Reading and Levell 1996; genetic depositional units in Collinson 1996). As discussed by Nanson and Croke (1992), in a specific period of time a river channel, and thus also a floodplain will change in response to environmental changes, whereby such floodplain changes may reverse in case of re-developing environmental conditions. Based on this principle, reversals in floodplain formation may be archived in fluvial records that allow for a reconstruction of the environmental evolution within the catchment.

To summarize, with respect to palaeoenvironmental conditions, fluvial sediment archives may record:

(1) information about processes responsible for archive formation that are derived from sediment characteristics (Reading and Levell 1996);
1 Introduction

(2) Information about post-sedimentary overprinting, such as soil formation processes (Collinson 1996, Zielhofer et al. 2009);

(3) Information about periods of action (e.g. Macklin et al. 2002).

An overriding issue belongs to the importance of different influencing factors for fluvial sedimentation dynamics. In addition to internal or intrinsic factors that are often considered as having substantial impact on floodplain evolution (Schumm 1972, 1979; Blum and Törnqvist 2000; Törnqvist 2007), climate is generally seen as the most important external forcing parameter (e.g. Vandenberghe 2003, see review in Fletcher and Zielhofer 2013). However, strong influence arises also from tectonics, base-level or sea-level changes, and human impact (e.g. Reading and Levell 1996, Vandenberghe et al. 2010) that often hinder a direct relationship between fluvial dynamics and climate. Taking all these factors into account, the question remains as to the nature of climate influences that cause reactions of fluvial systems, and how reactions to such impacts look like. Furthermore, the degree of influence of other parameters is a major issue. Further questions belong to matters such as response times between different systems that mediate between initial changes in the catchment area and processes affecting the receiving water floodplain, which also encompasses the question of sediment connectivity between these systems (Bracken et al. 2015).

1.3 Objectives and methodological approach

From chapters 1.1 and 1.3 an abundance of research question can be derived. Due to the fact, that no comprehensive and systematic work on floodplain sediments has yet been realized in the Atlantic part of Spain, the suitability of such sediments to reconstruct Late Pleistocene and Holocene environmental conditions was an initial question already during project initiation. As soon as the high potential and especially the favorable preservation conditions of floodplain sediments became evident, a number of follow-up questions were integrated in the work program. Finally, following main objectives can be drawn:

(1) In order to reconstruct fluvial dynamics for a Late Pleistocene and Holocene timeframe, the sedimentation history of Spanish River floodplains must be investigated.

(2) A careful catchment area analyses and characterization of local to regional physiographic conditions must be conducted to assess potential impacts of different influencing factors on fluvial dynamics.

(3) Causal relationships between specific influencing factors and landscape system reactions, i.e. fluvial system response, shall be identified with the final aim to link dynamic patterns to certain environmental conditions, and e.g. to separate human impact from climate forcing.
Relating to response behavior and time and duration of dynamics it is intended to assess supra-regional patterns as well as regional peculiarities to closer define the sphere of influence of specific factors and to work out some general principles regarding fluvial system response. A special focus will be on a possible coupling between large-scale climate fluctuations and phases of landscape development, in particular geomorphologic system behavior.

As a final remark, the obtained results will be discussed.

In view of these objectives it is essential to conduct research in different river catchments in Spain. Therefore, the first step will be to perform a number of detailed regional case studies, since, as already mentioned there are no previous studies to refer to. In a second step, these separate studies will be contextualized to gain supra-regional analyses and synthesized with regard to existing ideas and concepts.

As shown in chapter 1.1, the investigated river basins are located in areas of different precipitation regimes that range from 650 mm year\(^{-1}\) in lower Andalucía and 450 mm year\(^{-1}\) in the Madrid Basin. This configuration allows for examining the role of diverse quantities of annual precipitation for catchment erosion, sediment transport and floodplain deposition over time. Numerous concepts attach fundamental importance to the prevailing precipitation regime, when relating to sediment yield (e.g. Langbein and Schumm 1958, Walling and Kleo 1979, Lavee et al. 1998, Ruiz-Sinoga and Romero Diaz 2010) or high flood frequency (Bullón 2011). A likely assumption would envisage that a greater tendency towards dryness should be accompanied by an accentuation of hydrological events (especially precipitation and runoff) that likewise increases the reaction of geomorphologic systems. Thus, it is intended to examine whether the currently lower volume of precipitation in the Madrid Basin corresponds to different patterns of fluvial system response compared to the more humid southwest of Spain.

Another reason behind the selection of the study areas was the availability of suitable outcrops within the river floodplains. Usually natural sections of Holocene sediments are very rare in Atlantic river basins as no severe river incision affected the floodplains during the recent past. Fortunately, from 2009 until 2012 a very strong exploration activity took place within the lower Jarama River valley that is situated in the sphere of influence of the capital Madrid. Gravel mining related to the construction boom initially survived the financial crises that led to a strong increase of the number of gravel pits beside some pits that have already been running since the 1970ths. Therefore, and because of many good contacts with mining companies that have been established during the project duration, excellent conditions were found for analyzing a variety of outcrops in numerous different floodplain positions. Likewise in the lower Guadalete River valley, a large number of active gravel pits were found that were mainly operated by family businesses. Especially since it turned out that fluvial architectures of active floodplains in Spain are highly complex, the availability of appropriate exposure conditions was crucial to conduct detailed stratigraphic descriptions.
In the following, a short description of the methodological approach that is used to meet the above mentioned objectives will be provided. A flowchart of specific works is given in Figure 1.1.

The main focus in the course of data collection was on field work with the preliminary goal to develop a composite profile for each studied river floodplain. Several work steps include prospection, profile description, preparing of profile sketches and sampling for further laboratory analyses. An important aspect involves the appropriate identification of architectural elements (see chapter 1.2) within the profile sections as this provides a basis for subsequent interpretations of fluvial dynamics. Generally, different sediment units have been distinguished based on sedimentological and pedogenetic findings. Representative key-profiles were selected and sampled for soil physical, sedimentological and geochemical analyses. A detailed description of analyses conducted is presented in chapter 3.3 with a summary of methodologies and the significance of possible outcomes. The chronological resolution is based on radiocarbon dating of suitable organic material as well as carbonate mollusk shells. In the case of poor outcrop conditions as turned out in the lowermost Guadalete River valley, a drilling program provided stratigraphic results that were necessary to derive the composite profile. Concomitantly, a further geophysical method was applied by using electrical resistivity tomography (ERT) parallel to the coring sections. After composite profiles have been compiled for the study areas, it was feasible to reconstruct floodplain development and sedimentation history and to draw conclusions about fluvial behavior associated therewith.

In a next step, an extensive literature survey was conducted, with the aim of characterizing individual river catchments regarding the influence of possible factors, i.e. tectonic forcing, base-level changes, climate fluctuations, human activity and inherent dynamics, with the latter being largely intangible. If influencing factors have been identified, e.g. via the comparison with secondary archives that are sensitive to landscape development, potential impacts have been estimated and discussed. A focus of this dissertation is on the impact of climate and climate changes, therefore studies on climate sensitive archives of local and regional relevance have been used for a correlation with the elaborated fluvial records in order to discover possible interrelations between climate and geomorphologic system response. In this way, and under the careful consideration of other influencing factors, a detailed palaeoenvironmental history can be regarded as a final outcome of the individual regional studies.

In a subsequent advanced study, a supra-regional consideration of fluvial dynamics in Spain was implemented by comparing the regional studies. The main aim was to identify supra-regional patterns of floodplain dynamics with the intention to verify a coupling of large-scale climate fluctuations and specific phases of landscape evolution. For the purpose to clarify regional peculiarities of floodplain dynamics, again a survey of catchment characteristics was carried out. With reference to existing concepts that try to explain deviating responses of geomorphologic systems on external
Figure 1.1. Flowchart of the work plan that was implemented during the research process.
forcing, it was attempted to discuss differing onset, offset and duration, or even the absence of phases of landscape dynamics. Particular attention was paid to the issues of response times and buffer capacities of different river catchments.
2 Late Quaternary fluvial dynamics of the Jarama River

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Late Quaternary fluvial dynamics of the Jarama River in Central Spain

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Abstract: The Jarama River and its catchment provide a valuable natural archive to study and reconstruct past environmental conditions in central Spain. This region is highly prone to changes in the hydrological cycle under predicted climate warming in particular with respect to aridity periods, rainfall variability and the occurrence of extreme flood events. Here we present 15 exposures covering a time span of the last 44 ka, which were documented in the field and of which seven exposures were soil-chemical analyzed regarding soil texture, organic matter, as well as carbonate and iron content. Ages are based on radiocarbon dating on 32 samples. Latest Holocene sediments were found within the channel-belt, where permanent remobilization of sediments takes place due to the migration of the meandering river course. In more distal floodplain positions, sediment sequences show a complex fluvial architecture referring to periods of varying character and intensity of alluviation as well as periods of geomorphic stability indicated by soil formation. Furthermore, sedimentation patterns vary along different river sections. Aggradations of coarse gravels took place between ~40 and 18 ka cal BP over the entire valley floor. Alluviation of fine material was documented between 17 and 16, at ~7.5, between 5.1 and 3.3, at 2.8, between 2.1 and 1.5, at ~1.0, and around 0.4 ka cal BP until recent times. Astonishingly in late Holocene times, between 4.2 and 3.1 cal BP, aggradations of coarse gravels even in distal floodplain areas overlap with sedimentation of fine material in adjacent river sections pointing to a complex constellation of parameters involved. Periods of soil formation were detected around 43, at 31, between 16 and 12.6, after 7.5 until 5.1, between 2.8 and 2.1 and at times after 1.5 ka cal BP. Phases of geomorphic stagnation were found at
38 ka cal BP and for a duration of 200 years at 3.0 ka cal BP and refer to absent geomorphic or pedogenic processes. All these patterns are an expression of the interaction between climatic variations, tectonic impulses and human influences. A comparison with other terrestrial archives enabled us to reconstruct late Pleistocene and Holocene palaeoenvironmental conditions on a regional scale, and furthermore to link specific stages of floodplain development to prevalent influencing variables. Thus, with emphasis on the fluvial system response, we offer a model of a cause-and-effect relation that concentrates on rapid climate changes, long-lasting climatic deteriorations and the role of human interventions.

*Keywords*: central Spain, fluvial dynamics, Jarama River, Mediterranean, palaeoenvironmental conditions, terrestrial archives
2.1 Introduction

The Mediterranean region is highly sensitive to varying environmental conditions. The fragility of this area regarding even slight climatic changes and/or human interventions into the environment was subject of numerous research projects. Focal points of research are in particular process-related studies dealing with erosion-deposition mechanisms throughout different temporal and spatial scales (Lopez-Bermudez 1990, Brandt and Thornes 1996, and Butzer 2005) or studies on natural archives with the intention to assess future environmental developments, for instance in the context of a climate warming, based on environmental changes of the past (Luterbacher et al. 2006).

The main purpose is to find significant indicators or proxies that are able to reflect environmental changes over a certain period and that at best can be linked to specific environmental conditions. In this regard, the distribution and intensity of precipitation as consequence of climatic variability plays a decisive role in the buildup of the majority of Mediterranean terrestrial archives, especially in the context of erosion, transportation and sedimentation processes. Additionally, increasing efforts were made to identify linkages between former precipitation patterns and large-scale climate systems like the North Atlantic Oscillation (Rodrigo et al. 2000; Brayshaw et al. 2011).

Many endeavors have been done to unveil the relations between geomorphic systems and climatic influences in the Western Mediterranean including a vast number of terrestrial archives (see Fletcher and Zielhofer 2013 for a review, Roberts et al. 2011). Several studies of North Atlantic marine sediment cores (e.g. Bond et al. 1997, Bard et al. 2000, Naughton et al. 2009) revealed the impact of ice-rafting events on atmospheric circulation and climate changes that is apparently likewise reflected in numerous terrestrial archives (Mayewski et al. 1994, Zielhofer and Faust 2008, Zielhofer et al. 2010, Vegas et al. 2010, Moreno et al. 2012).

Continuous and meaningful palaeoenvironmental information can be expected of lake records or river floodplains with a sufficiently large catchment area. It is assumed that within large river catchments external influences, apart from tectonic impulses, need a certain scope to initiate geomorphic processes that find expression in the floodplain development (de Vente and Poesen 2005). Furthermore, fluvial systems are open systems and therefore able to trace not only conditions of sedimentation but also of erosion. Regardless of the applied scale, sedimentation in the floodplain needs erosion elsewhere in the catchment. The advantage of fluvial archives is the high significance of particular sedimentary layers. First of all its deposition already indicates the crossing of a critical geomorphic threshold. The structure and features of layers tell a lot about the sedimentary environment and the type and intensity of participating processes (Miall 2000, Reading 2009). Even if no or just a slight sedimentation has taken place, the development of alluvial soils gives evidence of stable geomorphological conditions within the floodplain (Zielhofer et al. 2009). A challenge of studying fluvial archives is still the identification of parameters that participated on their composition. Beside external factors like climatic and anthropogenic impact, also variables inherent to the system or tectonic events might have played a major role (Schumm 1973,
Late Quaternary fluvial dynamics of the Jarama River

2. Late Quaternary fluvial dynamics of the Jarama River

Gregory and Schumm 1987). If it is possible to determine concrete dependencies between influencing factors, fluvial archives contain a high potential to provide reliable information about palaeoenvironmental conditions (e.g. Houben 2003, Lespez et al. 2011), especially if they are related with archives of climate information in the strict sense such as travertine.

Concerning the spatial extent and the regional importance of its catchment, the Jarama River has so far received comparatively little attention. A few studies addressed early to middle Pleistocene terraces with an archeological or tectonic background (e.g. Santonja et al. 1980, Silva et al. 1988, Silva 2003). Further research of sedimentation dynamics of the Jarama was done by Alonso and Garzón (1994, 1996), but as most of the studied profiles were situated in the proximal channel belt area, they found predominantly gravels being accumulated during the Holocene.

Especially during the last years a vast number of new gravel pits have been established in the Jarama valley even in distal floodplain positions. By this, outstanding profile exposures were generated, sometimes over a distance of several hundreds of meters across the floodplain.

In this study, we present a secured standard stratigraphy for late Pleistocene and Holocene sediments of the Jarama River developed by geomorphologic, sedimentological and pedogenic findings. Beside field surveys on 15 profile exposures and intensive physical and chemical soil analyses, the chronological resolution is additionally confirmed by 32 radiocarbon dates. Our findings contribute to a better understanding of past fluvial dynamics in the Western Mediterranean and were discussed addressing a changing environment over the last 44 ka.

2.2 Study area

The Jarama River (Rio Jarama) is one of the most important watercourses in central Spain and comprises a catchment area of around 11.500 km² (Figure 2.1). The Jarama originates at an altitude of 2120 m a.s.l. in the Sierra de Guadarrama, a mountain range belonging to the eastern Spanish Central System that frames the Jarama catchment to the north. After 150 km crossing the Madrid Basin southwards, the Jarama flows into the Tajo River (Rio Tajo) at an altitude of 485 m a.s.l. Within the lower reach, the valley bottom of the river spreads to a width of 3 km and reveals fluvial sediment sequences reaching up to 14 m in depth. Due to the high altitude (500 - 800 m a.s.l.) in central Spain, the basin exhibits a distinct continental Mediterranean climate with mean annual precipitation of 456 mm and two rainfall maxima in the first half of the winter and in late spring (meteorological station in Madrid - 40°25´N/ 03°41´W) (Sträßer 1998). Land use within the Madrid Basin is dominated by scrublands, pastures and farmland. Cultivation activity mainly takes place in form of dryland farming and is limited by soil degradation and scarcity of rain.
2 Late Quaternary fluvial dynamics of the Jarama River

Figure 2.1. (A) Location of the study area in central Spain. (B) Overview of the Jarama River catchment area with drainage network and profile exposures. (C) Map section with studied profiles in the lowest section of the Jarama River.

2.2.1 Geological and tectonic background

The Madrid basin, an old tertiary depression, shows a succession of 800 m of Miocene sediments, which consist of arkosic alluvial fan material in the distal parts, lacustrine calcareous marls in the more central parts and gypsum marls in the formerly deepest areas of the depression (Alonso-Zarza et al. 1990, Calvo et al. 1996). At least since the Middle Miocene the Madrid basin is characterized by a severe tectonic activity (Andeweg et al. 1999) finally linked to the large-scale Betic compression. Numerous structures are known which are active up to present-day and which are often running parallel to the NE-SW orientated southern border of the Spanish Central System (De Vicente et al. 2007). With the initiation of a fluvial drainage in the upper Miocene, the river network began to incise intensively along such flexures leading to the recent drainage pattern (see Figure 2.1). The capability of the Miocene gypsum marls to halokinetic deformation and subrosion together with large bulging structures and a high seismic activity inside the Madrid basin resulted in extensive collapses within these marls during the Pleistocene (Silva et al. 1988, De Vicente et al. 2007). This was followed by strong river incisions and the development of steep escarpments, up to 60 – 80 m high. During the Pliocene large parts of the depression have been covered by the
Raña, a widespread alluvial fan deposit rich in coarse gravels, which can be seen as one of the main sources for the subsequent aggradations of fluvial terrace bodies within the Jarama river network.

2.2.2 Geomorphological setting of the Jarama valley

Along the upper and middle course, the predominant part of the Jarama floodplain is occupied by late Pleistocene terraces, in which the narrow Holocene floodplain is cut in (Alonso and Garzón 1994). Along the lower course, latest Pleistocene and Holocene terrace surfaces merge into one level and are not distinguishable by terrace steps (see geomorphologic map in Silva et al. 1988). Here, the Jarama is running through a floodplain with a gradient of 1.7 ‰ and widths ranging between 2 and 3 km. Until the beginning of the 20th century the lower Jarama River showed a meandering pattern with medium sinuosity, which was strongly reduced by discharge regulation and gravel mining since the 1950ies (Garzón and Alonso 2002). The recent channel has incised up to 4 - 5 m into the floodplain level. Actually, the river carries a sandy and gravelly bedload and builds up medium to coarse grained sand bars inside the averagely 100 m wide channel.

2.3 Methods

Fieldwork was carried out with focus on i) the stratigraphy of the floodplain sediments, and ii) the spatial distribution of specific sediment units. Between 2009 and 2011, 15 exposures were studied in the field and 243 soil and sediment samples were taken. Sedimentological and pedogenetic findings were used to differentiate between sediment units. The considerable horizontal lengths of the profile sections were used to identify i) erosive stratigraphic boundaries and ii) the onset of particular sedimentary layers. Representative key profiles were selected and sampled to confirm the field observations and to distinguish between soils and soil sediments in ambiguous cases.

Standard analyses were implemented in the laboratory of the Department of Physical Geography at the Technische Universität Dresden, Germany. Grain-size analyses were conducted in form of pipette analyses and wet sieve techniques (Schlichting et al. 1995) after dispersing with sodium pyrophosphate. As some samples contained a severe amount of gypsiferous marl-derived material, the soil suspension tended to flocculate due to high gypsum contents. Grain-size analyses first became possible, as initially the gypsum was eliminated by dilution and centrifugation of the respective samples (Frenkel et al. 1986, FAO 1990). The amount of gypsum and related salts that were dissolved is illustrated with the aid of shaded bars within the grain-size analytics (Figures 2.2, 2.4, 2.5 and 2.7).
Soil organic matter was measured via suspension and catalytic oxidation (TOC-VCPN / DIN ISO 16904). Carbonate content was determined by measuring the carbon dioxide gas volume after adding hydrochloric acid in a Scheibler apparatus (Schlichting et al. 1995, Zielhofer et al. 2009). Total iron content was determined after pressure digestion with concentrated nitric and hydrofluoric acid using atomic adsorption spectrometry. Pedogenic iron content was measured after dithionite extraction using atomic adsorption spectrometry as well (Schlichting et al. 1995, Zielhofer et al. 2009).

For confirming the correct absolute age of each sediment sequence, radiocarbon dating was carried out on 32 samples of in situ and ex situ charcoals, wood, organic sediments and bones (see table 2.1). The measurements were performed by the AMS 14C laboratories in Kiel (KIA) and Erlangen (Erl), Germany, and Miami (Beta, United States), and all 14C ages were calibrated using CALIB 6.0 (Stuiver and Reimer 1993) with the IntCal09.14c calibration curve (Reimer et al. 2009) that has been extended to 50 ka cal BP. The mean of the 2σ probability interval is usually used in the text and denoted in Table 2.1. All radiocarbon dating derived from existing studies were likewise calibrated in the above mentioned manner to ensure comparability.

Table 2.1 Radiocarbon dates obtained on late Pleistocene and Holocene sediment sequences of the Jarama River.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Lab no.</th>
<th>Material</th>
<th>14C age yrs BP</th>
<th>Cal. age BP (2σ)</th>
<th>Significance</th>
<th>Sediment unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aranjuez (AR-108)</td>
<td>Beta-293515</td>
<td>Organic sediment</td>
<td>26,150 ± 120</td>
<td>30,852 ± 279</td>
<td>Soil formation</td>
<td>2d</td>
</tr>
<tr>
<td>Aranjuez (AR-109)</td>
<td>Beta-293516</td>
<td>Branch</td>
<td>16,140 ± 70</td>
<td>19,193 ± 254</td>
<td>Filling of sinkhole</td>
<td>2e</td>
</tr>
<tr>
<td>Aranjuez (A2-10)</td>
<td>KIA 39205</td>
<td>Trunk (Populus sp.)</td>
<td>4475 ± 30</td>
<td>5132 ± 155</td>
<td>Start sedimentation</td>
<td>6a</td>
</tr>
<tr>
<td>Aranjuez (AR-X)</td>
<td>Beta-313498</td>
<td>Wood</td>
<td>3860 ± 30</td>
<td>4284 ± 126</td>
<td>Stagnant sedimentation</td>
<td>6a</td>
</tr>
<tr>
<td>Aranjuez (AR-65)</td>
<td>Beta-294964</td>
<td>Branch</td>
<td>3750 ± 40</td>
<td>4109 ± 125</td>
<td>Active sedimentation</td>
<td>6</td>
</tr>
<tr>
<td>Aranjuez (A2-9)</td>
<td>KIA 39206</td>
<td>Ex situ charcoal</td>
<td>3090 ± 30</td>
<td>3300 ± 78</td>
<td>Active sedimentation</td>
<td>9</td>
</tr>
<tr>
<td>Aranjuez (A2-2)</td>
<td>KIA 39204</td>
<td>Charred plant material</td>
<td>2925 ± 25</td>
<td>3089 ± 114</td>
<td>Stagnant sedimentation</td>
<td>8a</td>
</tr>
<tr>
<td>Aranjuez (AR-81)</td>
<td>Beta-294974</td>
<td>Branch</td>
<td>2870 ± 30</td>
<td>3007 ± 128</td>
<td>Stagnant sedimentation</td>
<td>8a</td>
</tr>
<tr>
<td>Aranjuez (A2-5)</td>
<td>KIA 39210</td>
<td>In situ fire site</td>
<td>2870 ± 25</td>
<td>2982 ± 93</td>
<td>Stagnant sedimentation</td>
<td>8b</td>
</tr>
<tr>
<td>Aranjuez (A2-4)</td>
<td>KIA 39209</td>
<td>Ex situ plant remain</td>
<td>2845 ± 25</td>
<td>2966 ± 95</td>
<td>Stagnant sedimentation</td>
<td>8a</td>
</tr>
<tr>
<td>Aranjuez (A2-1)</td>
<td>Beta-301970</td>
<td>Ex situ charcoal</td>
<td>2730 ± 30</td>
<td>2838 ± 77</td>
<td>Active sedimentation</td>
<td>9</td>
</tr>
<tr>
<td>Aranjuez (A2-26)</td>
<td>Erl-15157</td>
<td>Ex situ charcoal</td>
<td>2094 ± 41</td>
<td>2120 ± 171</td>
<td>Active sedimentation</td>
<td>10</td>
</tr>
<tr>
<td>Aranjuez (A2-25)</td>
<td>Beta-301971</td>
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<td>1610 ± 30</td>
<td>1484 ± 72</td>
<td>Active sedimentation</td>
<td>10</td>
</tr>
<tr>
<td>Aranjuez (A2-8)</td>
<td>KIA 39211</td>
<td>Ex situ charcoal</td>
<td>405 ± 25</td>
<td>423 ± 90</td>
<td>Active sedimentation</td>
<td>12</td>
</tr>
<tr>
<td>Cemex (Cem-120)</td>
<td>Beta-300818</td>
<td>Organic sediment</td>
<td>33,290 ± 220</td>
<td>37,972 ± 768</td>
<td>Stagnant sedimentation</td>
<td>2</td>
</tr>
<tr>
<td>Holcim (H-20)</td>
<td>Erl-15163</td>
<td>Ex situ charcoal</td>
<td>&gt; 53,500</td>
<td>43,789 ± 1502</td>
<td>Start soil formation</td>
<td>1a</td>
</tr>
<tr>
<td>Holcim (H-21)</td>
<td>Erl-15164</td>
<td>Ex situ charcoal</td>
<td>39,762 ± 1053</td>
<td>43,789 ± 1502</td>
<td>Start soil formation</td>
<td>1a</td>
</tr>
<tr>
<td>Holcim (H-18)</td>
<td>Erl-15162</td>
<td>Ex situ charcoal</td>
<td>13,654 ± 236</td>
<td>16,493 ± 898</td>
<td>Active sedimentation</td>
<td>3b</td>
</tr>
<tr>
<td>Holcim (H-17)</td>
<td>Erl-15161</td>
<td>Ex situ charcoal</td>
<td>10,599 ± 45</td>
<td>12,537 ± 113</td>
<td>Stagnant sedimentation</td>
<td>4b</td>
</tr>
<tr>
<td>Holcim (H-131)</td>
<td>Beta-301972</td>
<td>Ex situ charcoal</td>
<td>4460 ± 40</td>
<td>5093 ± 200</td>
<td>Colluvial layer</td>
<td>-</td>
</tr>
<tr>
<td>Peralta (P-31)</td>
<td>Erl-15167</td>
<td>Ex situ charcoal</td>
<td>2044 ± 39</td>
<td>2009 ± 109</td>
<td>Active sedimentation</td>
<td>10c</td>
</tr>
<tr>
<td>Peralta (P-22)</td>
<td>KIA 39218</td>
<td>Ex situ charcoal</td>
<td>2035 ± 30</td>
<td>2004 ± 104</td>
<td>Active sedimentation</td>
<td>10c</td>
</tr>
<tr>
<td>Peralta (P-24)</td>
<td>Erl-15166</td>
<td>Ex situ charcoal</td>
<td>1983 ± 39</td>
<td>1932 ± 104</td>
<td>Channel aggradation</td>
<td>-</td>
</tr>
<tr>
<td>Peralta (P-63)</td>
<td>Beta-313499</td>
<td>Ex situ charcoal</td>
<td>1960 ± 30</td>
<td>1908 ± 79</td>
<td>Active sedimentation</td>
<td>10a</td>
</tr>
<tr>
<td>Peralta (P-24/2)</td>
<td>Beta-300822</td>
<td>Bone collagen</td>
<td>1810 ± 30</td>
<td>1726 ± 97</td>
<td>Channel aggradation</td>
<td>-</td>
</tr>
<tr>
<td>San Martin (SM-30)</td>
<td>Erl-15169</td>
<td>Ex situ charcoal</td>
<td>386 ± 37</td>
<td>413 ± 96</td>
<td>Active sedimentation</td>
<td>13</td>
</tr>
<tr>
<td>San Martin (SM-29)</td>
<td>Erl-15168</td>
<td>Ex situ charcoal</td>
<td>307 ± 38</td>
<td>385 ± 89</td>
<td>Start sedimentation</td>
<td>13</td>
</tr>
<tr>
<td>Seseña (S-14)</td>
<td>Erl-15159</td>
<td>Ex situ charcoal</td>
<td>6595 ± 38</td>
<td>7498 ± 67</td>
<td>End sedimentation</td>
<td>5b</td>
</tr>
<tr>
<td>Seseña (S-15)</td>
<td>Erl-15160</td>
<td>Ex situ charcoal</td>
<td>3103 ± 33</td>
<td>3317 ± 75</td>
<td>Start soil formation</td>
<td>7c</td>
</tr>
<tr>
<td>Sotoguajares (Ce-28)</td>
<td>Erl-15165</td>
<td>Ex situ charcoal</td>
<td>&gt; 54,000</td>
<td>5152 ± 288</td>
<td>Active sedimentation</td>
<td>-</td>
</tr>
<tr>
<td>Titulcia (TT-121)</td>
<td>Beta-300823</td>
<td>In situ fire site</td>
<td>4490 ± 90</td>
<td>5152 ± 288</td>
<td>Soil formation</td>
<td>5</td>
</tr>
<tr>
<td>Titulcia (TT-122)</td>
<td>Beta-300824</td>
<td>Ex situ charcoal</td>
<td>1690 ± 30</td>
<td>1612 ± 81</td>
<td>Cultural layer</td>
<td>10</td>
</tr>
</tbody>
</table>
2.4 Fluvial architecture and characteristics of the sedimentary units

The lower Jarama valley shows a very complex sedimentary structure, while the homogenous floodplain surface shows neither terrace steps nor definable lateral limits of specific sediment units. However, the high density of gravel pits enabled the identification of four main chronostratigraphic sequences including 14 stratigraphic units spanning the last 44 ka. The first four units belong to the latest Pleistocene while 10 units reflect the Holocene floodplain evolution. The identification of all these units was hindered by complex sedimentation and erosion structures. Classical deposition features such as lateral terrace building were almost absent as only remnants of former terrace bodies were preserved.

2.4.1 Sequence 1 – Late Pleistocene (Holcim, Holcim-2 and Aranjuez profiles)

The late Pleistocene sediments of the Holcim and Holcim-2 profiles (Figure 2.2) occurred in the most distal positions in the western Jarama floodplain (Figure 2.1). High resolved topographic maps showed that these areas run with a wedge-like shape along the contact of the floodplain and the marginal escarpment of the marls, and thus are seen as terrace remnants. These positions are elevated beyond the recent channel bed with 6 or 7 m and dip with a low angle towards the Holocene sequences. They are almost covered by alluvial fans built up by arroyos running into the floodplain or by colluvial hill slope deposits. The arroyos are deeply incised into the steep escarpment of the Miocene marls.

Unit 1 and Unit 2: The most evident feature of Sequence 1 is a potent gravel body (Unit 2) consisting of poorly sorted but mainly clast-supported coarse gravels. In nearly every section, this layer is present with a thickness of 6 m (Figure 2.3A) showing a horizontal layering. Lenticular strata of gravels with a lateral expanse of several tens of meters interlock and generate a trough shape pattern. The lower limits of these lenses are erosion surfaces as they cut the other ones. Individual lenses are up to 2 m thick consisting of several gravel layers (50 cm) that are separated by thin sandy layers. Occasionally, cross-stratified sand layers with a thickness up to 50 cm are interposed.

This Unit 2 is regarded as braided stream deposit. Hence, it has been accumulated simultaneously in multiple channels, which are reflected by the single lenticular units. Perhaps, the distinguishable gravel layers indicate individual phases of discharge meanwhile the sands have been accumulated in relation to declining discharge values.

The gravels appear quasi sterile regarding datable material. A maximum age of $43.79 \pm 1.5$ ka cal BP is provided by a $^{14}$C-dating of underlying sediments (Unit 1) that were found at the base of the Holcim-2 profile (Figure 2.2). Generally, Unit 2 overlies
Figure 2.2. Sedimentary sequences and sediment units of the profiles (A) Holcim (location: 40°04'29" N and 3°38'16" W) and (B) Holcim-2 (location: 40°04'01" N and 3°38'24" W). The legend refers to all other profiles (Figures 2.4, 2.6 and 2.7).
grayish marls at the basis of the sequence, but in the Holcim-2 profile we found a reddish ochre-brown material of loessic origin (Unit 1a) below the erosive surface. Similar material was redeposited in the Tajuña valley and in large parts of the Tajo valley (Figure 2.1). Both catchments are characterized by abundant late Pleistocene loess depositions. The material of Unit 1a consists of gypsum-cemented silty loam with sporadic occurrences of well-rounded clasts. The upper limit bears a reddish dark brown soil with a thickness of 30 cm, showing humic enrichment and slight decalcification. A $^{14}$C-dating of a charcoal below the soil refers to an age of $43.79 \pm 1.5$ ka cal BP (see Table 2.1). The loessic material underwent certain deformation as it is overlaid by a bented gravel layer. This boundary layer forms a sinkhole 5 m deep and 50 m wide that was chaotically refilled by a grayish loam rich in gravels and charcoals (Unit 1b) together with a considerable proportion of gypsum (~43%). The strong addiction of the marls to halokinetic deformation and subrosion is obvious as mentioned in chapter 2.2.1. Unit 2 shows just slight deformations, mainly in the area of the Holcim profile.

**Particular appearance of Unit 2 in the Aranjuez profile:** In the Aranjuez profile, Unit 2 can be divided into four subunits. Obviously, Unit 2 underwent a strong deformation prior to the deposition of the Holocene sequence (Figure 2.3B & 2.4). The layers are heavily folded and structures of diapirism as well as sinkholes appear. A branch found in the chaotic infill of such a sinkhole in the uppermost part of Unit 2e exhibits a radiocarbon age of $19.19 \pm 0.25$ ka cal BP (Table 2.1). While Unit 2b and 2e are primarily characterized by coarse gravel accumulations, Unit 2c and 2d show a completely different appearance. A series of large lenticular sediment bodies, comprised of clayey loams above cross-stratified sands refers to a depositional age of about $30.85 \pm 0.28$ ka cal BP (Figure 2.4, Table 2.1). A following period of stability and associated soil formation can be seen in the field and is proofed by analytics (Figure 2.4). A comparable accumulation of grayish clays is found in the Cemex profile (not shown) and was accumulated at about $37.97 \pm 0.77$ ka cal BP (radiocarbon dating, Table 2.1).

**Unit 3:** In the Holcim profile (Figure 2), Unit 3 is characterized by a homogeneous layer of reddish sandy loam, which shows a strongly rubefied soil in its upper section, partly with remnants of a humic horizon. The soil has a reddish brown color and shows evidences of bioturbation and intense illuviation of dark brown clay into pores and cavities. Especially in the upper part an enrichment of secondary precipitated gypsum, derived from Unit 4 above, took place. A $^{14}$C-age was taken from the middle of the unit and dates to $16.49 \pm 0.9$ ka cal BP (Table 2.1). Fe(d)/Fe(t)-ratios indicate a slight increase of values towards the upper part of the soil and an abrupt drop within Unit 4 (Figure 2.2). Principally, this illustrates the potential of Fe-oxides in soils to indicate weathering processes. But in most other profiles the initial Fe(t)-contents of the sedimentary layers are extremely fluctuating even within the same layer (distribution curve of Fe(t), Figure 2.4, 2.5 & 2.7), which makes a useful interpretation of the data very difficult (cf. Zielhofer et al. 2009).
Late Quaternary fluvial dynamics of the Jarama River
Figure 2.3. Profile sections perpendicular to the Jarama river course. (A) Late Pleistocene sequence of the Holcim-El Puente profile section showing the lateral extent of the Younger Dryas alluvial fan (Unit 4) and the covering with colluvial deposits of the Roman period (Unit 10). Sample numbers reflect the sequence shown in the Holcim profile (Figure 2.2A). (B) Aranjuez profile section showing the late Pleistocene sequence in the lower part (Unit 2) that was subject to strong deformations, including dolines and diapirs. Above the pronounced unconformity the sequence of mid-Holocene gravels and late Holocene sands and flood loams is following.

In the lowest part of Unit 3, arch-shaped fine to medium-sized gravel lenses, 20 cm deep and a few meters wide (Unit 3a; Figure 2.3A, right side) were found. They refer to rapidly shifting channels in front of an extensive and homogeneous deposition of the sandy layer of Unit 3b. A distinctive change of the fluvial dynamics must have happened leading over from the braided stream deposition to the extensive sedimentation of sandy loams with the final end of sedimentation and decoupling of distal floodplain areas from active river processes. Referring to the age the subsequent soil formation took place in a time between 16.49 ± 0.9 ka and 12.54 ± 0.11 ka cal BP (Figure 2.3A).

Unit 4: The lowermost part of Unit 4a most likely consists of translocated soil material of Unit 3 and indicates the onset of a denudation period (Figure 2.2). At about 12.54 ± 0.11 ka cal BP the accumulation of a fine laminated alluvial fan started in the Holcim profile (Unit 4b; Figure 2.3A). As the alluvial fan was fed by the surrounding gypsum marls, the alternating layers contain up to 63 % of gypsum. Visible are small fissures with a vertical displacement of about 1 cm that could indicate post-sedimentary tectonic activity. The sedimentation of Unit 4b is characterized by thin laminar washing-processes. Two layers of relocated gypsum-rich but more homogeneous material are following with nests of small pebbles at the basis (Unit 4c). A yellowish brown color, humic enrichment and stronger aggregation indicate soil formation within this Unit 4c fan material.

2.4.2 Sequence 2 – Early to Mid-Holocene (Seseña and Titulcia profiles)

Unit 5: After a longer period without sedimentary evidences, Unit 5 is characterized by Holocene accumulations, which date back to ~7.5 ± 0.07 ka cal BP in the Seseña profile (Figure 2.5, Table 2.1). Sands (Unit 5a) and sandy loams (Unit 5b) are found in the proximity of the late Pleistocene sequences and reach to the borders of the active channel belt where they have been reworked by the meandering channel. Generally, Unit 5b does not exceed a vertical expansion of 1 meter. In the upper part it shows a soil formation with slight clay enrichment and a weak aggregation (Figure 2.5). This soil has a dark pale black-brown color and contains a lot of gypsum nodules. A \(^{14}C\) dating of a fire place on top of the soil indicates a time of exposure at least until
5.15 ± 0.29 ka cal BP (Figure 2.5, Titulcia profile). Due to the vulnerability of charcoals to erosion processes, sedimentation is expected to have started shortly after.

During this time the rubefied soil of Unit 3 in the Holcim-2 profile was capped by a series of blackish colluvial layers that filled a shallow depression (Figure 2.2). Beside a certain amount of reddish coarse-grained brick fragments and a fragment of a stone tool, a large amount of charcoal was found within this layer, which was dated to 5.09 ± 0.2 ka cal BP. Furthermore, the colluvium filled in a small settlement pit that was dug into Unit 3.
Figure 2.5. Sedimentary sequences and sediment units of the profiles Titulcia (location: 40°06′39″ N and 3°36′59″ W), Seseña (location: 40°04′60″ N and 3°37′18″ W) and San Martin (location: 40°12′28″ N and 3°33′12″ W). For legend see Figure 2.2.
Unit 7: The sediments of Unit 7 are characterized by a relatively low but continuous accumulation until 3.32 ± 0.08 ka cal BP (Seseña profile, Unit 7c). After a sandy layer that refers to stronger dynamics (Unit 7a), an alternate stratum of sandy and clayey loams with a dark brown color and increased organic content is following (Figure 5, Titulcia profile). Unit 7 finish up with a strong soil formation characterized by subangular and angular soil aggregates, intense root penetration and abundant gypsum nodules. Indications of human influence are missing.

2.4.3 Sequence 3 – Mid-Holocene to Roman period (Aranjuez, Peralta, Seseña and Titulcia profiles)

Unit 6 and Unit 8: A special case of depositional features is expressed by the Aranjuez profile (Figures 2.3 and 2.4) as some of the sediment units are unique in the study area. Above the already mentioned late Pleistocene section, a Holocene gravel body (Unit 6) was accumulated subsequent to a large hiatus of several thousand years. This unit was detected over a distance of 600 m parallel and perpendicular to the rivers flow direction. It consists of horizontally stacked gravel lenses, altogether 3 m deep. The lowest part is characterized by boulders of more than 20 cm in diameter. This unit exhibits a lower limit that constitutes a marked erosive surface. Occasionally underlying accumulations of grayish clayey sands are rich in macro fossils and charcoal. A large waterlogged trunk of a poplar tree (Populus sp.) originating from the lower Unit 6 shows a $^{14}$C-age of 5.13 ± 0.16 ka cal BP (Figure 2.4, Table 2.1). A smaller waterlogged branch was well preserved in a clayey sand layer and date back to 4.28 ± 0.13 ka cal BP. Besides uncertainties of the radiocarbon dating, this disparity indicates a longer retention time of the trunk within the active system and a reversal of the dynamics after 4.28 ± 0.13 ka cal BP. The aggradation of Unit 6 proceeded apparently in a multiple channel pattern, since no evidences of lateral channel movement appear. Additionally, this is supported by the simultaneous termination of the aggradations, which resulted in an undulating surface of the gravel body. Four radiocarbon dates confirmed that a grayish clayey material capped this gravel body over a broad area at about 3.0 ka cal BP (Figure 2.3 and 2.4, Unit 8). This clay is regarded as waning flood deposit. It predominantly occurs in trough positions and occasionally, it appears as a sequence of black and humic laminations. Most likely, it accumulated in a setting shortly after the abrupt abandonment of the multiple channels, when the river infrequently splashed over the whole floodplain without transporting coarser material. A last gravelly channel-fill is visible in Figure 2.3 (right) and dates 3.01 ± 0.13 ka cal BP at the basis. At the same time, crevasse splays in form of thick sand bars reached even distal areas of the floodplain and partly intermesh with grayish humic clays. Botanical macro fossil analyses from a clayey layer at the basis of this last channel-fill are shown in Figure 2.6. Beside a proportion of 20 % of pine (Pinus sp.) the wood samples exhibit a predominance of riparian vegetation comparable to present conditions.
Charcoal samples are well-rounded but relatively large, which points to relocation over short distances.

**Unit 9:** A further peculiarity in the Aranjuez profile is expressed by a huge homogeneous layer of loamy sand (Unit 9). The sands are rather unstructured and allow no inner differentiation, which suggests a relatively quick accumulation at about 2.84 ± 0.08 ka cal BP (Figure 2.4, Table 2.1). Subsequently, a mature floodplain soil developed until maximal 2.12 ± 0.17 ka cal BP (Figure 2.4). It features a dark red brown color, sub-angular structuring and increased clay content in the upper part. Gypsum and carbonate precipitations are abundant and root channels reach down to basal gravels. The lower part of Unit 9 shows intensive hydromorphic features.

**Unit 10:** After a sharp boundary, a very distinct sediment layer is following (Unit 10). It is mostly a darkish soil sediment layer with a high content of ceramics and artifacts. In the Aranjuez profile, this sediment shows strong aggregation and thin bright coatings of gypsum at the aggregate surfaces. The uppermost part shows a pedogenic enrichment of clay and organic content (0.61 %, Figure 2.4) and is gypsum-free. From top to bottom the gypsum content increases to 17 %, indicating strong leaching processes. This leaching is also reflected by the gypsum accumulation in Unit 9 below, where gypsum content of up to 7.8 % can be attributed to secondary gypsum precipitation. Prominent features are numerous fragments of reddish and pale bricks and ceramics, as well as a vast number of gravel-sized floating stones. According to two radiocarbon dates (Figure 2.3), the accumulation started shortly before 2.12 ± 0.17 ka cal BP and ended shortly after 1.48 ± 0.07 ka cal BP. In the uppermost part pedogenetic features indicate a certain time of exposure.

In the Titulcia profile Unit 10 has a light grey color and consists of more than 50 % of gypsum (Figure 2.5). Certainly that is because of the peripheral position within the
floodplain surrounded by gipsy marls. A high amount of brick and pottery fragments (e.g. terra sigillata) and a $^{14}$C-age of 1.61 ± 0.08 ka cal BP (Figure 2.5, Table 2.1) prove these sediments to be of Roman age. An accumulation of Roman burial sites in the close proximity to the Titulcia profile supports this finding.

The uppermost layer of the Holcim profile (Figure 2.2) is likewise comprised of colluvial sediments (Unit 10). Along its lower erosion surface, several settlement pits were observed up to 2 m deep and filled with coarse pale bricks. Unit 10 contains plenty ceramic fragments and dates presumably into the Roman period.

A further occurrence of Unit 10 is indicated by the Peralta profile (Figure 2.7 and 2.8). This profile can be differentiated into a lower sandy section, a succession of loamy and sandy layers in the middle part, and a coarse-grained cover in the uppermost part. Even if several periods of geomorphic stability and humic enrichment can be identified, the high density of $^{14}$C-dating (Figure 7, Table 2.1) indicates an extremely fast development of the whole sequence. That means that the major part was accumulated in the range of one century around 2.0 ka cal BP. However, no artifacts or ceramics were found within the Peralta profile.

Unit 11 and Unit 12: In addition, the loamy material of Unit 11 and Unit 12 belongs to Sequence 3. Unit 11 (Aranjuez and Titulcia profiles) finish with a humic A-horizon, which suggest a sedimentation period midway between 1.48 ± 0.07 ka and 0.42 ± 0.09 ka cal BP (Figure 2.4, Table 2.1). The more reddish loams of Unit 12 (Aranjuez profile) do not show evidences of pedogenetic processes, and probably mean a fast deposition of Unit 13 in close succession to Unit 12. In contrast to Unit 10, Unit 11 and Unit 12 do not show gypsum enrichments, which might indicate another sediment provenance.

2.4.4 Sequence 4 – Little Ice Age (San Martin, Aranjuez and Seseña profiles)

Unit 13 and Unit 14: A last period of an above-average degree of fluvial dynamics took place around 0.39 ± 0.09 ka cal BP and is indicated by a quick accumulation of reddish sandy and silty layers (Unit 13) in the San Martin profile (Figure 2.5, Table 2.1). Internal differentiation is possible but reflects rather fluctuations in intensity of a relatively constant proceeding sedimentation. Deposits of reddish-yellow sandy loams cover nearly the entire floodplain with a depth of up to 0.5 m (Aranjuez and Seseña profiles). The expanded sedimentation of such coarse-grained material in terms of planar sheet-like crevasse splays illustrates the high-energy setting during this sedimentation period.

The top layer is represented by typical brown flood loam (Aranjuez, Seseña, Titulcia and San Martin profiles) that was accumulated until the recent past (Unit 14).
Figure 2.7. Sedimentary sequence and sediment units of the Peralta profile (location: 40°21'21" N and 3°28'54" W). For legend see Figure 2.2.

Figure 2.8. Profile section of the Peralta profile. Sample numbers reflect the sequence shown in the Peralta profile (Figure 2.7).

Further sequences identified in the field are of modern ages showing a loamy character and included modern time’s artifacts (e.g. ammunition of the 20th century). They were located within the active channel belt, where such sequences are permanently deposited and reworked due to channel meandering.
2.5 Interpretation - Stages of floodplain development

In fluvial systems many characteristics generally refer to periods of activity, to transition periods or to periods of stability of the entire geomorphic system. Therefore, the purpose is to identify responsible parameters leading to the setup of a specific sedimentary signal in the respective fluvial archive (cause and effect). In this study, we identified several stages of floodplain development, which were illustrated in Figure 2.9. Additionally, our stratigraphic findings were cross-matched with 26 spatially related proxy records, i.e. pollen archives, aeolian deposits, flood deposits and lake sediments (Figure 2.10) to unveil possible causalities of the Jarama catchment development. Radiocarbon dating mentioned in these studies was calibrated according to chapter 3 in order to ensure comparability with our own findings. Especially reliable information of archives reflecting climatic relevance was used to detect the influence of climate on fluvial dynamics. Due to the high density of studies on terrestrial archives in central Spain, it was possible to reconstruct factors and influences based on these secondary archives and thus gain independent parameters. Finally, the effort is to reconstruct palaeoenvironmental conditions on a regional scale and to assess its impact on fluvial system behavior. However, trans-regional comparison, especially concerning different types of archives, must be done with care, also because prevalent environmental conditions in Spain may change over short distances.

2.5.1 Extensive aggradations during Marine Isotope Stage (MIS) 3 (44 – 30 ka cal BP)

Before or around 43.79 ± 1.5 ka cal BP (mid-MIS 3) loess accumulations took place within the Jarama catchment, including a subsequent relocation of loessic material into the large river valleys. Additionally, the slight soil formation on top of Unit 1 indicates a period of more geomorphic stability. Similar observations were described by Ruiz Zapata et al. (2009) about 80 km downstream at the Tajo River, where approximately between 44 and 41.5 ka BP (based on OSL-ages) reworked loessic material was deposited in a fluvial/aeolian setting (Figure 2.10g). As information about the MIS 3 is scarce, only a few pollen analyses from lake or cave sediments were considered. An arid period is detected by Vegas et al. (2010) around 46 ka cal BP in the Campo de Calatrava (central Spain) (Figure 2.10v), and by Burjachs and Julia (1994) between 49.5 and 46.2 ka BP (based on U-series analyses) in Catalonia (north Spain) (Figure 2.10u) and refers to favorable conditions for extensive loess deposition. A glacial retreat followed after 48 ka BP (based on \(^{10}\)Be dating) as described by Jalut et al. (2010) for north Spain (Figure 2.10s) and Lewis et al. (2009) recorded strong arising fluvial dynamics due to large glacial melt water discharges in north-east Spain at around 47 to 45 ka BP (based on OSL-ages). The temperate and humid interstadial between 46 ka and 41 ka BP found by Burjachs and Julia (1994) (Figure 2.10u) and Burjachs et al. (2012) or between 44.5 and 43.5 ka BP (Sanchez Goni et al., 2000) coincides with the
Figure 2.9. Schematic sketch of the evolutionary development of the Jarama River floodplain during late Pleistocene and Holocene times.
Late Quaternary fluvial dynamics of the Jarama River

Figure 2.9. (continued).
deposition and pedogenic superimposing of Unit 1. Simultaneous, a clear-out (c.f. Thorne and Osman 1988) in terms of lateral river erosion occurred as Unit 1 is just partly preserved in a small depression, that was formed by a subsidence within the basal gypsum marls (cf. Luzon et al. 2008, Galve et al. 2009).

A strong shift towards a high energy drainage pattern was detected some time before 37.97 ± 0.77 ka cal BP (Unit 2a, 2b). Accumulation of a massive gravel body, i.e. braided river deposits, is linked to highly variable discharge values with high runoff peaks as well as sediment mobilization and transport (c.f. Vandenberghhe 2003). Gravels, mainly derived from older Pleistocene terraces, were accumulated in shifting river channels and fine material passed through or was cleared out afterwards. These gravel aggradations were interrupted at least twice by the accumulation of a clayey sediment around 37.97 ± 0.77 ka and 30.85 ± 0.28 ka cal BP (Unit 2d) (Figure 2.4, Table 2.1) according to 14C-dating of the bulk organic fraction of these sediments. Such clayey layers are a constantly recurring feature also in Holocene times, and were treated as an ecological marker. We interpret them as waning flood deposits. A careful interpretation of this Unit 2d points to a change in the discharge patterns towards lower runoff values. Runoff was presumably restricted to individual small channels and clayey sediments were accumulated during single flooding events. Despite the apparent decrease of discharge, this period around 30.85 ± 0.28 ka cal BP involved a distinct soil formation that was also proven by laboratory analyses (Figure 2.4). For such a pedogenesis we assume more humid conditions during this period. Even if we try not to overemphasize this Unit 2d, it should be noted that there are several studies on terrestrial archives that reflect climate anomalies around 31 ka BP (e.g. Vegas et al. 2010 (Figure 10v); Valdeomillos, 2005). A possible connection to large-scale atmospheric events cannot be excluded (Bond et al. 1997, Bard et al. 2000, and Frigola et al. 2008).

2.5.2 Increased fluvial activity in the course of the Last Glacial Maximum (LGM) (30 – 18 ka cal BP)

After a period of stability indicated by a soil formation after 30.85 ± 0.28 ka cal BP (Figure 2.4), further gravel aggradations took place in the Jarama valley. Conclusions on depositional features are difficult due to strong post-sedimentary deformations (Figure 2.3B). The termination of Unit 2e can be localized between 19.19 ± 0.25 ka and 16.49 ± 0.9 ka cal BP (Figure 2.2, Figure 2.4, and Table 2.1). Most obvious, the period of the LGM had a determining influence on the deposition of Unit 2e. Globally, the LGM was chronologically constrained between 26.5 and 19 ka BP (Clark et al. 2009). In central Spain, the maximum glaciations belonging to the LGM were dated between 25 and 19 ka BP (cosmogenic 36Cl dating) in the Sierra de Guadarrama (Palacios et al. 2012) and between 26 and 21 ka BP (cosmogenic 36Cl dating) in the Sierra de Gredos (Palacios et al. 2011) (Figure 2.10k), both framing the Jarama catchment. Jalut et al. (2010) stated cold and dry conditions between 32 and 18 ka BP in north-west Iberia (Figure 2.10s) and Pons and Reille (1988) found similar conditions between
Late Quaternary fluvial dynamics of the Jarama River

28 and 18 ka cal BP in south Spain (Figure 2.10t). Recent studies on up to 8m thick loess deposits in a distance of about 40 km point to an Optical Stimulated Luminescence age of loess sedimentation from about 35 to 25 ka BP (Wolf et al. in prep.). Hence, the accumulation of Unit 2e took apparently place under cold and arid conditions, perhaps in terms of braided river deposition and associated highly variable discharge pattern with high runoff peaks and without supply limitation.

Particular emphasis is assigned to the radiocarbon age of 19.19 ± 0.25 ka cal BP, which was gathered in the context of a quickly refilled funnel-like sinkhole in the underlying marls (Figure 2.3B). For the development of sinkholes in the gypsum environment of the Ebro basin, average subsidence rates point to 2 mm/year in mid- to late-Pleistocene times (Luzon et al. 2008) and 2.5 to 10 cm/year for currently active processes (Soriano and Simon, 1995). Numerous sinkholes in the Aranjuez profile point to a much faster solution of the gypsum with simultaneous down-dragging of Unit 2 gravel layers and a chaotic refill of the sinkholes. Flowing groundwater is important for the solution of gypsum. Thus, the relatively fast sinkhole development along with further evidences like gypsum diapirism could indicate a period of increased humidity due to the remoistening of the system in the sequel of the LGM termination.

2.5.3 Sand deposits (Unit 3) at the end of MIS 2 (18 – 12.6 ka cal BP)

Due to the absence of structural differentiation, the sandy loams of Unit 3b are considered to refer to a fast and homogeneous alluviation around 16.49 ± 0.9 ka cal BP. They do not show lateral variations and the sand fraction is dominated by quartz.

Concerning climatic signals, terrestrial archives in S- and central Spain indicate cold and arid conditions between 17 and 16 ka BP (Pons and Reille 1988 (Figure 10t), Gil Garcia et al. 2002 (Figure 2.10p), Vegas et al. 2010 (Figure 2.10v)). However, further evidences for enhanced fluvial dynamics, i.e. alluviation, in this period are known from the Manchega Plains (Rendell et al. 1994) (Figure 2.10h), the Tajo River (Benito et al. 2003a) (Figure 2.10a) and between 22 and 18 ka BP from north-east Spain (Lewis et al. 2009). Such dynamics must be linked to an activation of the discharge system. Assuming that the climate was generally arid in this time, the higher discharge could be associated with glacial retreat. In north-east Spain glacial retreats are documented from 18 to 13.5 ka cal BP with a slight warming in the first period leading to a fast melting of the Pyrenean glaciers between 17 and 15 ka BP (primarily based on 10Be-dating) coinciding with major sedimentary changes in glacial lakes in the Pyrenees (Jalut et al. 2010) (Figure 2.10s). For the Jarama catchment most rapid glacial retreats were found between 16 and 15 ka BP (36Cl-dating) in the Sierra de Gredos and Sierra de Guadarrama (Palacios et al. 2011, Palacios et al. 2012) (Figure 2.10k). Possibly, the accumulation of the sandy Unit 3b took place at the beginning and during the strongest melting of the deglaciation period. Generally, such phases of climatic transition are
Figure 2.10. Summary of the late Quaternary fluvial sedimentation history of the Jarama River in central Spain and differentiation of deposition (D) and soil formation (S) periods are visible in the upper part. The lower part shows a comparison with terrestrial records from Spain, containing information about late Pleistocene and Holocene variability of temperature and humidity, as well as geomorphic responses of various systems to environmental changes. Information were strongly generalized and partly abstracted. All radiocarbon dates were initially calibrated using the IntCaL09.14c calibration curve (Reimer et al. 2009). The map below shows the locations of the listed archives on the Iberian Peninsula. a: High-magnitude flood periods of the Tajo River, central Spain (Benito et al. 2003a, b). b: High-magnitude flood periods of several river systems in Spain (Benito et al. 2008). c: Periods of increased floodplain aggradations in Spain (Benito et al. 2008). d: Flood period with increased discharges of the Jarama River based on historical data, central Spain (Uribelarrea et al. 2003). e: High-magnitude flood periods of the Guadiana River, southwest Spain (Ortega and Garzón 2009). f: Alluvial sedimentation periods in the Bardenas Reales NP, northeast Spain (Sancho et al. 2008). g: Periods of aeolian loess deposition and fluvial deposition of reworked loess in middle Tajo Basin, central Spain (Ruiz Zapata et al. 2009). h: Phases of fluvial and aeolian sand deposition and periods of soil formation in the San Juan Alluvial Plain, south-central Spain (Rendell et al. 1994). i: Period of aeolian sand deposition in the Sierra de Guadarrama, north-central Spain (Bateman and Diez Herrero 2001). j: Phases of aeolian sand deposition in the Duero Basin, north-central Spain (Bateman and Herrero 1999). k: Periods of maximal
glacier advance and fastest glacial retreat in the Sierra de Gredos, central Spain (Palacios et al. 2011); the color gradient indicates the onset of deglaciation. l: Periods of accumulation of slope deposits (cold and wet climate conditions) and periods of down-cutting (warm and dry climate conditions) in northeastern Spain (Gutiérrez-Elorza and Peña-Monné 1998). m: Reconstruction of climate changes based on numerous proxies derived from peat bogs, lake sediments, colluvial sediments and soils in northwest Spain (Martínez-Cortizas et al. 2009). n: Variations of temperature and humidity identified in a pollen record in the wetlands of Las Tablas de Daimiel, south-central Spain (Dorado Valiño et al. 2002). o: Abrupt climatic change leading to an ecological crisis for one century deduced from palaeoanthropological and archaeological data in the Amblés Valley, central Spain (López-Sáez et al. 2009). p: Periods of climatic variation identified in pollen sequences in the Sierra de Cebollera, northern Spain (Gil García et al. 2002). q: Climatic fluctuations deduced from palaeoecological indications as well as lake levels and desiccation periods of the lake Siles in the Sierra Segura, south-central Spain (Carrión 2002). r: Climatic variations based on vegetation changes derived from pollen sequences from Villaverde in the Sierra Segura, south-central Spain (Carrión et al. 2001). s: Climate changes during the last deglaciation phase derived from pollen sequences of Villaseca and La Mata palaeolakes in the Cantabrian Range, northwest Spain (Jarut et al. 2010). t: Differentiation of climate phases based on pollen records from the peat bog of Padul, southern Spain (Pons and Reille 1988). u: Climate changes during the last glaciation on the basis of pollen analyses in a travertine sequence in northeast Spain (Burjachs and Juliá 1994). v: Sequence of cold-arid and warm-arid phases documented in the sedimentary record of the Fuentillejo maar-lake at Campo de Calatrava, central Spain (Vegas et al. 2010). w: Succession of arid and humid periods derived from geochemical analyses of the Zoñar lake varve record, southern Spain (Martin-Puertas et al. 2009). x: Climatic phases based on ostracode assemblages of the Lake Salines sediment record, southeast Spain (Roca and Juliá 1997). y: Palaeohydrological and climatic variations deduced from the sedimentary record of Lake Estanya, northeast Spain (Morellón et al. 2008). z: Climate phases of the late Holocene based on multi-proxy analyses of the Somolinos lake sediment record, central Spain (Carrás et al. 2012); by archaeological data a strong human impact is proven 100 yrs after the climate change at 2.1 ka BP.

associated with phases of system instability. Diminished vegetation cover, higher runoff, sediment mobilization and floodplain sedimentation are characteristics during these phases and are discussed by Schumm (1973) and Vandenberghhe (1995, 2002, 2003). The lack of further accumulations could be linked to the arrival of stability due to progressing climatic improvement and vegetation succession.

The progressive amelioration of climate during the Bølling/Allerød is well documented in form of the strongly rubefied soil formation on Unit 3. For that, geomorphic stable conditions with absent floodplain sedimentation and presumably lacking sediment mobilization due to re-established vegetation cover were required. Reddish iron compounds of pedogenic hematite could be indicative for increased temperatures (Torrent and Barrón 2003) and a stronger drying up of the soil material. Higher temperatures and increased humidity during that time are known for almost whole Iberia (e.g. Pons and Reille 1988 (Figure 2.10t), Perez-Obiol and Julia 1994, van der Knaap and van Leeuwen 1997, Carrión 2002 (Figure 2.10q), Gil García et al. 2002 (Figure 2.10p), Carrión et al. 2010, and Jalut et al. 2010 (Figure 2.10s)).

In conclusion, the Jarama River responded to the late-glacial warming with intense alluviation between 17 and 16 ka cal BP (Oldest Dryas?) followed by markedly stable conditions expressed by prolonged soil formation during the Bølling/Allerød.
2.5.4 Younger Dryas and Early to Mid-Holocene sedimentation (12.6 – 7 ka cal BP)

Younger Dryas: Evidences for the Younger Dryas (12.9 – 11.5 ka cal BP; Alley 2000, Rasmussen et al. 2006) appear as large fine-laminated alluvial fans covering the Bølling/Allerød floodplain soil (Unit 4) (Figure 2.3A) in distal floodplain positions. According to the \(^{14}\)C-dating of a charcoal, the fan formation started around 12.54 ± 0.11 ka cal BP (Figure 2.3A). As the fan material originates from the surrounding tertiary gypsum marls, more than 60 % of the fan material is comprised of gypsum or related salts. For the time between 12.5 and 11.5 ka cal BP, cold and arid climate conditions in central Spain were reported by Bateman and Herrero (1999) (Figure 2.10j), Dorado Valiño et al. (2002) (Figure 2.10n), Gil Garcia (2002) (Figure 2.10p) and Vegas et al. (2010) (Figure 2.10v). It is conceivable that the fan formation, and thus the erosion of the gypsy marls were closely associated with a severe temperature and moisture decrease during the Younger Dryas that resulted in a diminished vegetation cover. The end of the fan formation remains chronologically unresolved and at least two units of slope deposits overlie Unit 4. Since human influences are absent, we date these accumulations into the early Holocene.

 Interruption of sedimentation until 7500 cal BP: Concerning fluvial dynamics, after the deposition of Unit 3 a prolonged hiatus prevents from reconstructing fluvial sedimentation dynamics during the Pleistocene/Holocene transition. The first fluvial signals of the Holocene, i.e. the sandy and loamy Unit 5, occurred at around 7.5 ± 0.07 ka cal BP. Possible scenarios for the time until 7.5 ka cal BP can be either erosion and clearing out of sediments or temporary sedimentation followed by a complete remove. Generally, after the Younger Dryas a development towards warmer and more humid conditions is observable in Spain (Pons and Reille 1988 (Figure 2.10t), Roca and Julia 1997 (Figure 2.10x), Dorado Valiño et al. 2002 (Figure 2.10n), Gil Garcia et al. 2002 (Figure 2.10p), Franco-Múgica et al. 2005, and Martínez-Cortizas et al. 2009 (Figure 2.10m)). Various studies on terrestrial archives documented the development of climate and geomorphic activity periods during the early Holocene (see Figure 2.10). As early Holocene sediments are lacking in the Jarama Valley, it is questionable which environmental conditions caused rather erosion (or stagnation) than sedimentation during that time. Possible explanations are:

(1) An early Holocene stabilization took place due to warm and humid conditions (Martínez-Cortizas et al. 2009 (Figure 2.10m), Faust and Díaz Del Olmo 1997). Abundant vegetation minimized sediment supply within the catchment and reduced runoff. But even if strong meander shifting would have led to a rapid floodplain turnover rate (Richards et al. 2002) older sediments should be at least partially preserved. However, despite the fact that we did not find early Holocene sediments we cannot prove its complete absence.
Alternatively, a high river gradient and sufficient precipitation could have led to the development of a multiple channel discharge pattern. For instance, Vandenberghe (2008) emphasized the potential of rivers to erode in the case of supply-limitation, high peak runoffs and intense lateral movement. In such a case, fine sediments passed through or were permanently washed out.

A third explanation may be linked to the high-magnitude flood periods recorded by Benito et al. (2003a) (Figure 2.10a) for example, between 10.5 and 10.2 ka cal BP or 9.5 and 9.3 ka cal BP. Possibly a few extreme flood events were sufficient to clear-out the fine sediment cover of the lower Jarama valley.

Onset of Holocene floodplain sedimentation: For the sedimentation of Unit 5 (chapter 2.5.5), the radiocarbon dating of 7.5 ± 0.07 ka cal BP corresponds with the upper end of a high-magnitude flood period recorded by Benito et al. (2003a) (Figure 2.10a) between 7.7 and 7.4 ka cal BP along the middle Tajo River. The question is, if this flood period is rather linked to the clear-out prior to the Unit 5 sedimentation or if it is linked to the sedimentation itself.

Numerous studies unveiled a strong environmental change for this time in Spain. Carrión (2002) (Figure 2.10q) and Jalut et al. (2009) (Figure 2.10s) describe a phase of transition in the Sierra Segura, which was characterized by a change from arid to humid conditions. Preece (1991) and Benito Calvo et al. (1998) describe similar conditions for the upper Jarama catchment. A contradictory finding by Dorado Valiño et al. (2002) (Figure 2.10n) shows a transition from humid to more arid conditions in the Manchega Plain and Vegas et al. (2010) (Figure 2.10v) documented a cold spell with high aridity between 7.5 and 7 ka cal BP. However, a higher runoff leading to flood events and sediment mobilization seems quite related to the transitional phase of such a climatic change (Knox 2000).

2.5.5 Mid-Holocene warm period and climatic collapse (7 – 5 ka cal BP)

A period of floodplain stability lasted at least until 5.15 ± 0.29 ka cal BP (Figure 2.5) accompanied by soil formation and river meandering. Assuming a time of exposure of almost 2 ka, the floodplain soil is poor developed. Although pedogenic features are visible in the exposures, the analytical proof is less decisive (Figure 2.5). We think that the attendant circumstances were not favorable to intense soil formation, as even some Pleistocene soils show stronger development. A hampering influence on soil forming processes could result from high contents of gypsum. Consistent gypsum contents of the upper Unit 5 horizons in the Titulcia profile (Figure 2.5) could be indicative for weak leaching caused by a low moisture regime. Thus, weak pedogenic features support rather arid conditions during this period.

Preece (1991), Benito Calvo et al. (1998), Carrión (2002) (Figure 2.10q) and Gil Garcia (2002) (Figure 2.10p) reported humid conditions at least until 5.9 ka cal BP in central Spain, changing into arid conditions afterwards. Also Sancho et al. (2008)
Late Quaternary fluvial dynamics of the Jarama River

(Figure 2.10f) described arid conditions in the Ebro basin at the beginning of 5.9 ka cal BP. Dorado Valiño et al. (2002) (Figure 2.10n) found an aridity trend until approximated 5 ka BP and Temiño et al. (1997) and Bateman and Diez Herrero (1999) (Figure 2.10j) proofed aeolian activity under hot and arid conditions around 6.5 ka BP (14C- and thermoluminescence-dating) in the Duero basin. No extreme floods occurred (Benito et al., 2003a) (Figure 2.10a) until the appearance of low-magnitude floods within the Duero basin around 4.8 ka cal BP (Benito et al. 2008) (Figure 2.10b). Carrión et al. (2007) detected an increase of xerophytes between 5.4 and 4.8 ka cal BP in the Sierra de Baza. Probably at least since 6 ka cal BP an increasing aridity prevailed in central Spain. A fluctuating river discharge must be assumed whereas high-magnitude floods are not reported. The initiation of floodplain sedimentation around 5.1 ka cal BP possibly point to an exceeded threshold caused by increasing aridity (see also Carrión 2002 (Figure 2.10q), Carrión et al. 2007, Martínez-Cortizas et al. 2009 (Figure 2.10m), and Vegas et al. 2010 (Figure 2.10v)). Also the colluvial deposit at the Holcim-2 profile falls within this time of system reevulsion (see chapter 2.4.2). However, the occurrence of numerous artifacts within these colluvial deposits is the first clear evidence of human occupation within the sedimentary record and could be interpreted as a first human impact that influenced the river system.

2.5.6 Highly dynamic floodplain aggradations and 3.0 ka cal BP-aridity crisis

(5 – 3 ka cal BP)

The dominant process during this period was the sedimentation of the valley floor. Finer material was accumulated on distal floodplain positions (Unit 7) and the proximal channel-belt area was characterized by extensive accumulation of coarse gravels (Unit 6). Astonishingly, in the lowermost river section the active channel-belt spread over almost the entire floodplain (Figure 2.9).

Deposition in distal floodplain positions started probably shortly after 5.15 ± 0.29 ka cal BP as indicated by a dated fire place (Figure 2.5). Assuming that superficial charcoals are susceptible to erosion and transport, sedimentary covering must have taken place a short time after. Sedimentation of Unit 7 stopped just after 3.32 ± 0.08 ka cal BP according to a 14C-dating in the Seseña profile (Figure 2.5). This Unit can be divided into different layers. Basal sands indicate an abrupt rise of dynamics, while following flood loams show a more steady sedimentation. These loams are interpreted as soil sediments with alternating episodes of accumulation and again soil formation. The duration of sedimentation processes is a matter of speculation. A well-developed soil in the upper part of Unit 7 (Figure 2.5) gives evidence for at least several centuries of floodplain stability associated with soil formation.

A different development was found in the Aranjuez profile, where the upper surface of the Pleistocene Unit 2 gravels shows a pronounced erosion unconformity (Figure 2.3B). Covering gravels (Unit 6) are reminiscent of a braided river depositional pattern and indicate an abrupt rise of river dynamics. Scattered sand lenses at the lower
boundary yielded a radiocarbon age of 4.28 ± 0.13 ka cal BP, which is considered as the onset of gravel aggradations. Gravel deposition stopped at around 3.09 ± 0.11 ka cal BP. We assume extensive erosion prior to the aggradations of the Unit 6 gravels (cf. Vandenberghe, 2008). Coarse gravels in the lowermost part of Unit 6 (Figure 2.3B) could have been acting as “erosion weapons”, which would support our assumption. By all appearances, basic preconditions regarding such particular river dynamics are closely linked to tectonic movements within the river valley that are related to the tertiary gypsum marls. As a result of such tectonic movements during the Pleistocene as well as the Holocene the longitudinal profile of the Jarama Valley shows sections of high river gradient and sections of low river gradient (Silva et al. 1988). Such a juxtaposition of different river gradients may have caused different sedimentation and erosion patterns within adjacent river sections even under the same palaeoenvironmental conditions (cf. Schumm 1973). Thus we found loamy floodplain sediments (Unit 7) in one section and coarse gravel deposits (Unit 6) in the other section, both Units extending over nearly the entire floodplain. Beside the precondition of a tectonic movement, primary arid conditions combined with high discharge variability and discharge peaks are considered to be the cause of the highly dynamic sedimentation patterns between 5 ka and 3 ka cal BP. It remains unknown, if other sections along the Jarama River showed similar dynamics during this period or if this development can be regarded as a site-specific peculiarity of a system response to overlapping influencing factors (Lane and Richards 1997, Houben 2003). Nevertheless, despite the contribution of tectonics, the lowermost river section (Aranjuez profile) exhibits clear phases of floodplain development. Therefore, an interpretation in terms of changing environmental conditions should be taken into account.

Considering numerous comparative studies, fluvial dynamics of the Jarama River between approx. 5.3 and 3.5 ka cal BP could be related to arid climate conditions that were found by Rendell et al. (1994) (Figure 2.10h), Carrió et al. (2001) (Figure 2.10r), Carrió (2002) (Figure 2.10q), Gil Garzia (2002) (Figure 2.10p), Dorado Valiño et al. (2002) (Figure 2.10n), Jalut et al. (2009) and Martinez-Cortizas et al. (2009) (Figure 2.10m). Main characteristics of this period were the material supply due to slope destabilization and the highly variable discharge due to a pronounced Mediterranean climate. Periods of high-magnitude floods between 4.2 and 3.4 ka cal BP found by Benito et al. (2008) (Figure 2.10b) and Ortega and Garzón (2009) (Figure 2.10e) support the assumption of an arid climate with strong rainfall variability and hence accentuated river discharges. Increased aridity from 3.6 ka cal BP onwards is described for the southern La Mancha Plain in Villaverdes (Carrió et al. 2001) (Figure 2.10r), the western La Mancha Plain at Las Tablas de Daimiel (Dorado Valiño et al. 2002) (Figure 2.10n) and the Avila Range in central Spain (Lopez-Saez et al. 2009) (Figure 2.10o), whereas Rendell et al. (1994) found soil formation between 3.5 and 3.0 ka BP (luminescence-dating) only 60 km east of Las Tablas de Daimiel (Figure 2.10h). This soil formation was likewise observed in the Jarama valley in distal floodplain positions around Seseña and Titulcia profiles (Figure 2.5) after 3.32 ± 0.08 ka cal BP.
At 3.0 ka cal BP a drastic event took place, lasting for about 200 years and leading to absolute stagnation of geomorphic processes within the lower Jarama floodplain. The multiple stream discharge pattern collapsed, the channels felt abandoned and a grayish humic and clayey sediment was deposited (Figure 2.3B) probably during sporadic flooding of the gravelly riverbed. Apparently, no soil formation took place and the large amount of charcoals could be indicative for a high fire frequency (role of charcoal fragments in fluvial sediments is e.g. discussed in Linstädter and Zielhofer (2010)). Comparable to counterparts in late Pleistocene sequences (Unit 2d) we attribute pronounced aridity to this period causing almost a breakdown of discharges. For instance, Thorndycraft and Benito (2006) and Benito et al. (2008) (Figure 2.10b and c) found a consistent absence of fluvial signals, i.e. floodplain sediments and slack water deposits, around 3.0 ka cal BP over entire Spain. For the same period, increasing aridity was documented by Roca and Julia (1997) (Figure 2.10x), Carrión (2002) (Figure 2.10q), and Dorado Valiño et al. (2002) (Figure 2.10n), and Rendell et al. (1994) even described intense aeolian sand deposition in the La Mancha Plain (Figure 2.10h). Zielhofer et al. (2010) conclude that likewise in Morocco more arid conditions prevailed between 3.2 and 2.7 ka cal BP. But in contrast to patterns in central Spain, the flood frequency significantly increased around 3 ka cal BP in northern Africa (see also Faust et al. 2004, Zielhofer et al. 2008)

2.5.7 Extensive sand deposition at 2.8 ka BP and following floodplain stability (3–2.1 ka cal BP)

After the aridity crisis at 3.0 ka cal BP the geomorphic stagnation phase ended just before 2.84 ± 0.08 ka cal BP with the deposition of a sandy layer in the Aranjuez profile (Unit 9) (Figure 2.4). Comparable to the late Pleistocene Unit 3, all indications point to a fast sedimentation at about 2.8 ka cal BP. Other archives revealed a transition from arid to humid conditions around 2.9 ka cal BP in east Spain (Roca and Julia 1997 (Figure 2.10x), Gutiérrez-Elorza and Peña-Monnè 1998 (Figure 2.10l, based on archaeological sites and 14C-dating)), and around 2.6 ka cal BP in central Spain (Carrión 2002 (Figure 2.10q), Currás et al. 2012 (Figure 2.10z)) with the wettest period between 2.5 and 2.14 ka cal BP (Martín-Puertas et al. 2009) (Figure 2.10-x). This transition correlates with a climatic shift towards cold conditions, detected at 2.8 ka cal BP over the North Atlantic (van Geel et al. 1996, Bond et al. 1997). For the Avila Range, directly to the west of the Jarama catchment, López-Sáez et al. (2009) documented an abrupt climatic change at 2.8 ka cal BP, leading to a transition from arid and warm conditions to a cold and humid period resulting in a century-long ecological crises (Figure 2.10o). Increased humidity caused the decline of pine and oak forests and the rainfall induced higher erosion as well as sedimentation within the valleys. Also Preece (1991) reported slope deposits in the upper Jarama catchment at that time. The sandy alluviation in the lower Jarama valley took place during a period of ecological transition and landscape fragility around 2.8 ka cal BP. It is possible that during the
previous arid period vegetation was destabilized, which in turn favored sediment mobilization after a rapid climate change towards very humid conditions. However, it must be taken into account that especially in the lowest river section (Aranjuez profile, Figures 2.3 and 2.4) the tectonic history changed the relief configuration significantly that also could have had influences on sedimentation dynamics during these times.

Later, until shortly prior to 2.12 ± 0.17 ka cal BP, the floodplain was characterized by stability and soil formation. Very humid and temperate conditions resulted in a strongly developed cambisol (Figure 2.4). Hydromorphic features in the lower subsoil point to sufficient water-availability. Regarding the intense soil formation, this period must be considered to be one of the most stable and humid periods during mid- to late Holocene times.

2.5.8 Flood loam accumulation during the Roman epoch (2.1 – 1.5 ka cal BP)

Shortly before 2.12 ± 0.17 ka cal BP a remarkable change of the sedimentary behavior took place, indicated by character and appearance of the floodplain sediments. In the Aranjuez profile, flood loams of Unit 10 are blackish, showing a priori raised clay contents (>40 %) and contain numerous ceramics and brick fragments, as well as floating stones (Figure 2.4). Anthropogenic impact is obvious. The oscillating upper surface could be indicative of frequent reversals of erosion and accumulation along secondary floodplain channels. That could explain occasional agglomerations of pebbles and gravels, as well as the large time span that is covered by the deposition of Unit 10 (Figure 2.4). Main delivery areas for the sediments of Unit 10 were the surrounding slopes consisting of Miocene marls, which is indicated by a gypsum content of up to 17 % within the sediments. Abundant colluvial deposits enriched with artifacts (see Holcim profile; Figure 2.3) are evidences that the floodplain was fed by slopes during the Roman period. In many sites across Spain anthropogenic influence was found after 2.0 ka cal BP (e.g., Allen et al. 1996, Santos et al. 2000, Carrión 2001 (Figure 2.10r), and Rubiales et al. 2007). In the lower Jarama valley, the accumulation of Unit 10 lasted at least until 1.48 ± 0.07 ka cal BP, which actually post-dates the Roman occupation. We think that during this period different deposits were accumulated in times of extraordinary pressure on the environment. For example, in the Peralta profile 3m of sediments were accumulated in only a few decades around 2.0 ka cal BP (Figures 2.7 and 2.8). Concerning the factors involved, a climatic shift from humid to arid conditions was reported between 2.3 ka and 2.12 ka cal BP (Gutiérrez-Elorza and Peña-Monné 1998 (Figure 2.10l), Carrión 2002 (Figure 2.10q), Martín-Puertas et al. 2009 (Figure 2.10w), and Currás et al. 2012 (Figure 2.10z)), which finally pre-dates the heavy sedimentation at Peralta. Currás et al. (2012) presented a sediment record of the Somolinos Lake in the upper Jarama catchment and found a climate-driven reduction in moisture availability at 2.12 ka cal BP (Figure 2.10z). Furthermore, a period with enhanced soil erosion was identified one century later, which was found to be triggered by forest clearings and land use changes due to an intense Roman colonization phase.
This time span coincides with the deposition of the Peralta sequence. The flood loam in this sequence (upper part of Unit 10; Figure 2.7) consists of clayey to silty material with high humic content and represents the counterpart to enhanced soil erosion within the catchment. However, solely based on sediment character, a dominant influence cannot be stated so far neither of the climate nor of human activity.

Another phase of environmental pressure must have occurred around 1.61 ± 0.08 ka cal BP when a strongly slope affected deposit enriched with artifacts was accumulated at the Titulcia profile (Figure 2.5). Also the Aranjuez profile shows accumulation of loam riddled with bricks at 1.48 ± 0.07 ka cal BP (Figure 2.4). In the eastern part of the Titulcia pit, Roman burial sites and Roman Terra sigillata pottery were found below 1 to 2m of flood loam deposits, indicating the Roman utilization of the floodplain area. A relationship between the 1.6 ka old slope deposits, the covering of the Roman sites on the floodplain-level and the end of the Roman epoch is speculative but seems comprehensible in a temporal point of view. In fact, during the considered timeframe the barbaric invasions (Visigoth period; López-Merino et al. 2009) and the decline of the Roman Empire coincide with the occurrence of the Dark Ages Cold Period. This change to more arid climate at around 1.6 ka cal BP (Carrión 2002 (Figure 2.10q), Martín-Puertas et al. 2009 (Figure 2.10w), and Currás et al. 2012 (Figure 2.10z)) with a strong reduction of temperature (Gil Garcia et al. 2007, Martín-Chivelet et al. 2011) quasi introduced the time of collapse of the Roman Empire.

2.5.9 Alternating flood loam accumulation and soil formation during the Medieval period (1.5 – 0.4 ka cal BP)

The upper part of Unit 10 shows certain indications of soil formation that point to floodplain stabilization at least for a few centuries (Figure 2.4). The following floodplain sediments (Unit 11 and 12, Aranjuez and Titulcia profiles) were accumulated until 0.42 ± 0.09 ka cal BP (Figure 2.4). Due to a lack of dating and since the comparison and evaluation of intensities of the soil formation within Unit 10 and 11 (Figures 2.4 and 2.5, Titulcia profile) remain difficult, we positioned the accumulation of Unit 11 in the period between 1.0 to 0.9 ka cal BP, which coincides with the period of enhanced flood frequency between 1.1 and 0.8 ka cal BP in the Tajo valley (Benito et al. 2003a (Figure 2.10a), Benito et al. 2003b, and Benito et al. 2008 (Figure 2.10b)). The clayey and humic character of the flood loam demonstrates the human influence in a way of maintaining an open landscape for cultivation, which enabled topsoil erosion. However, despite human pressure on the environment, the systems were able to stabilize indicated by soil formation in the floodplain sediments of Unit 10 and 11.
2.5.10 Accentuated fluvial dynamics during the Little Ice Age and recent flooding (0.4 – 0 ka cal BP)

The sedimentation of the flood loams of Unit 12 introduced a highly dynamic period of flooding and deposition only a few decades later. Shown in the San Martin profile (Figure 2.5), the channel-belt was filled up by a reddish-ochre sandy material (Unit 13) that extended even to distal floodplain positions (Figure 2.4, Aranjuez profile). A certain lamination with interposed silty layers refers to fluctuations of intensity during the flooding events.

According to Thorndycraft and Benito (2006) and Benito et al. (2003a) (Figure 2.10a) a higher flood frequency is documented for the Tajo River between 0.5 and 0.45 ka cal BP and for the headwaters of the Tajo River between 0.5 and 0.3 ka cal BP by Moreno et al. (2008). Historical documents show a concentration of flood events in Aranjuez between 0.41 and 0.31 ka BP (Uribelarrea et al. 2003 (Figure 2.10d), Benito et al. 2003b, and Bullón 2011) and even in the lower Guadiana River high-magnitude floods were recorded during that time (Ortega and Garzón 2009) (Figure 2.10e). Concerning associated climate conditions, after the “Medieval Warm Period”, lasting from 1.0 to 0.5 ka cal BP (Gil Garcia et al. 2007, Garcia-Hidalgo et al. 2007) a climatic deterioration induced the Little Ice Age, a cold period that was reflected in terrestrial archives in many parts of western Europe (Fletcher and Zielhofer 2013) and northern Africa (Faust et al. 2004). Numerous studies consider this as a period of prevailing wet conditions (Rodrigo et al. 1999, Morellón et al. 2008 (Figure 2.10y), and Fletcher and Zielhofer 2013) and occasional highest precipitation and runoff values (Benito et al. 2008 (Figure 2.10b), Moreno et al. 2008, and Bullón, 2011) leading to catchment erosion, flooding and floodplain sedimentation.

Modern times are characterized by river meandering and flood loam sedimentation. The uppermost layers of the floodplain sediments can be assigned to a period of intense land use and soil erosion in the catchment. Several periods of high-magnitude flooding are documented for the last centuries (Benito et al. 2003a, Benito et al. 2003b) (Figure 2.10a) that included the potential to cause extensive floodplain sedimentation. Within the channel-belt, terrace bodies comprised of clayey and sandy loams are inset and recently dissected. Findings like modern bricks and ammunition designate them to be of younger ages (e.g. El Porcal profile, not shown).

2.6 Human influence versus climatic control factors

An aim of this work is to differentiate between natural processes and human interventions and to state the role of climate and climate changes in terms of affecting geomorphic systems and processes. Floodplain sedimentation requires a degree of sediment mobilization within the catchment that can be human or climate induced. Especially in the case of rapid climate changes (RCCs) (Mayewski et al. 2004), a
delayed adaptation of vegetation may lead to diminished vegetation cover and hence, result in an increased sensitivity towards erosion processes. As discussed above, several periods of short but intensive sedimentations in the Jarama valley seem to be linked to RCCs. For example, the 2.8 ka-cold event caused a crossing of a geomorphic threshold, and hence a fast and dynamic response with strong sedimentations in the lowest river section. Sedimentation periods of the Jarama River are shown in Figure 10 associated with probable climatic dependencies in form of climate changes and climate variability documented by other terrestrial archives with regional relevance. In addition, coincidences of sedimentation periods in the Jarama valley and extreme flood events in the Tajo valley (Benito et al. 2003a) (Figure 2.10a) as well as in other Spanish river catchments (Benito et al. 2008) (Figure 2.10b) were compiled. Of particular importance is the way of sediment mobilization. If heavy rains affect an intact vegetation cover, this may prevent from extensive topsoil erosion, leading to linear erosion pathways and probably supply-limitation. Both climate as well as human induced thin out of vegetation cover initiates sediment supply to the floodplain during heavy rainfall. In fact, the establishment of open spaces is a basic requirement for sediment supply, since the distribution of material is mainly affected by heavy rains. Hence, a simultaneous appearance of floodplain sedimentation and extreme flood events finally supports the dominance of climatic parameters (Knox 2000, Benito et al. 2008) or at least a mixed signal of climate and humans. In the case of extensive floodplain sedimentation without the record of extreme flood events, as happened between 2.0 and 1.5 ka cal BP (see also Thorndycraft and Benito 2006) a significant participation of anthropogenic forcing becomes rather likely. Nevertheless, the amount of rainfall controls the processes of erosion as well as the connectivity of erosion pathways that is crucial to conduct sediments into the receiving rivers (c.f. Faust and Schmidt 2009). At least since the Roman colonization around 2.0 ka cal BP, the Jarama catchment is strongly influenced by clearing activities and farming (Moreno et al. 2008, Currás et al. 2012). Especially, character and appearance of sediments were modified as surrounding marls were activated through cultivation, and eroded topsoil material with settlement remains reached the floodplain. The uppermost parts of the Sierra de Gredos underwent little changes by human activities during the Roman period. During the Visigoth period after 1.5 ka cal BP the anthropogenic influence was intensified (López-Merino et al. 2009). Studies in the Avila Range situated in the northern part of the Spanish Central System document deforested landscapes already during the Late Bronze Age around 3.2 ka cal BP (López-Sáez et al. 2009). Many studies assume anthropogenic influence in Spain since 2.5 ka cal BP (Gutiérrez-Elorza and Peña-Monné 1998, Carrión 2002, and Martín Puertas et al. 2009) or already thousands of years earlier (Carrión et al. 2007, Martínez-Cortizas et al. 2009), however, a serious impact on geomorphic systems before 2.0 ka cal BP is mostly negated.
2.7 Significance of fluvial records in a spatial context

For the purpose of environmental reconstruction, fluvial archives constitute an important element. Priority is given to individual signals of a fluvial record and the ability to provide information about specific palaeoenvironmental conditions. Fluvial dynamics are usually the result of complex functional interactions of particular subsystems, and admitting a minimum size of catchment, fluvial archives provide the potential to reflect significant characteristics of environmental conditions rather than local phenomena. Considering the overlay of individual parameters, impulses to the fluvial system can strengthen or alleviate. This leads to certain selectivity of impulses responsible for the build-up of a fluvial record. Depending on the robustness of a system at a definite time, particular events may not cause a signal in the archive. Hence, they are not detected, which does not mean that they have not occurred. Schumm (1973) mentioned the difficulty to correlate number, magnitude and duration of erosional and depositional events, even within the same valley, as fluvial response to external influences varies even along reaches of one river. This can be due to different constitutions and delayed crossings of geomorphic thresholds in different reaches.

Considering the diversity of climatic and physiographic facilities on a trans-regional scale, the comparison of fluvial archives may highlight mainly differences than similarities (see Figure 2.10f and o). If different river catchments reveal evident similarities within their fluvial records, that would, for instance, indicate comparable process regimes, perhaps caused by the same external influence, like large-scale climatic configurations superimposing local conditions.

In this study we contextualize our own findings with published archive interpretation in order to give better insight into landscape evolution and manifestations of palaeoenvironmental conditions (Figure 2.10). Further research is necessary to understand different reactions of archive-generating systems to internal and external factors. Moreover, varying response times of different systems play a decisive role in understanding the occurrence of geomorphic activity and stability as reaction to specific influences.
2.8 Conclusion

The late Quaternary fluvial sedimentation history of the Jarama River may help to understand landscape evolution in terms of geomorphic activity and stability and its controlling factors during the last 44 ka. In order to reconstruct successive palaeoenvironmental conditions for the late Pleistocene and Holocene a comparison of different archives was conducted. As landscape evolution is closely linked to changing climatic conditions, which, themselves, are subject to strong spatial changes, the resulting model of landscape evolution represents a regional pattern for central Spain. The role of climate is to provide transport capacity in form of rainfall causing runoff. Runoff as well as sediment yield are controlled by the vegetation cover and arise generally from climatic deteriorations (aridification) or from human interventions. Following scenarios were deduced from the fluvial record of the Jarama River.

1. In a period of assumed sufficient availability of rainfall, resulting in high runoff and a well-developed vegetation cover, like during the early Holocene until 8 ka cal BP, the systems seems to show supply-limitation and hence, discharges caused erosion and out-clearing of the valley floor.

2. In the case of rapid climate changes, the system is put into a state of highest fragility. Nevertheless, as obvious in the periods between 17 and 16 ka, at 2.8 ka and at 0.4 ka cal BP, the system adapted relatively fast to new conditions and re-stabilized, which is indicated by a very restricted period of sedimentation. That means that an initial phase of intense sediment shifting was replaced by another state of supply-limitation.

3. A further possibility of system response emerges from a long-lasting weakening of the environment. Dynamics between 5.1 and 3.1 ka cal BP are linked to a pronounced Mediterranean climate with increasing aridity and rainfall variability. Dynamics since 2.0 ka cal BP show human-induced alterations due to clearing activity, agricultural land use and land use changes. A common feature of both periods is a thin out of the vegetation cover and a higher erosion risk. Therefore catchment erosion and floodplain sedimentation are always given during these periods, but finally erosive rainfall is necessary to initiate these processes. That means phases of active sediment shifting should be linked to phases with a high frequency of erosive rainfall events. In fact, the palaeoflood records of the Tajo River (Benito et al. 2003a, Benito et al. 2003b, Benito et al. 2008) show a certain degree of conformity between high-magnitude flood events and periods of floodplain sedimentation in the Jarama Valley between 5.1 and 3.5 ka cal BP as well as from 1.0 ka cal BP to the present. Consequently, floodplain sedimentation during times of absence of extreme flood events (e.g. between 2.1 and 1.5 ka cal BP in this study) could indicate an increase of human pressure on the environment. However, even in the case of most evident anthropogenic contribution, corresponding fluvial signals generally must be considered as mixed signals of human and climatic origin.
Acknowledgement

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References


Dorado Valiño, M., Valdeolmillos Rodríguez, A., Blanca Ruiz Zapata, M., José Gil Garcia, M., de Bustamante Gutiérrez, I., 2002. Climatic changes since the Late-glacial/Holocene transition in La Mancha Plain (South-central Iberian Peninsula, Spain) and their incidence on Las Tablas de Daimiel marshlands. Quaternary International 93-94, 73–84.


2 Late Quaternary fluvial dynamics of the Jarama River


Houben, P., 2003. Spatio-temporally variable response of fluvial systems to Late Pleistocene climate change: a case study from central Germany. Quaternary Science Reviews 22 (20), 2125–2140.


Late Quaternary fluvial dynamics of the Jarama River


2 Late Quaternary fluvial dynamics of the Jarama River


2 Late Quaternary fluvial dynamics of the Jarama River


3 Late Pleistocene and Holocene fluvial dynamics of the lower Guadalete River

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Fluvial system response to external forcing and human impact - Late Pleistocene and Holocene fluvial dynamics of the lower Guadalete River in western Andalucía (Spain)

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Abstract: The 170 km long river course of the Guadalete River (western Andalucía) provides an excellent record of Late Pleistocene and Holocene fluvial sedimentation dynamics. Furthermore, its floodplain sediments are very well suited to describe geomorphic changes forced by climate fluctuations, sea-level changes, tectonic influences and human activity. Multi-proxy investigations were based on field mapping and the study of 18 profile sections, mainly including sedimentological characterization, soil-chemical analyses and radiocarbon dating of 34 samples. Findings were complemented by drillings and electrical resistivity tomography. The lowermost 50 km river section can be divided into an upper and lower part (each 25 km long), based on different sediment preservation conditions. The boundary corresponds to the disparition of the Late Pleistocene river terrace. Significant floodplain aggradation occurred at around 10000 cal. a BP, while dynamics were strongly affected by sea level fluctuations until the early Holocene. Furthermore, sedimentation starting at 8000, 6100, 4600, 2200, 900 and 400 cal. a BP refers to enhanced fluvial dynamics due to environmental pressure that was presumably triggered by climate fluctuations, i.e. aridification. However, strongest intensity of sedimentation at 400 cal. a BP points to climate anomalies in the course of the Little Ice Age. In contrast, several periods of stability associated with alluvial soil formation took place during the Bølling and Allerød interstadials, prior to 8000, 6100 and 5100, and after 4300 and 2000 cal. a BP. The anthropogenic signal in floodplain evolution is not clearly distinguishable from that of climate. However, human land use had the potential to amplify geomorphic processes, especially during periods of climate deteriorations that caused increasing pressure on the environment.
3.1 Introduction

Numerous endeavors have been made to resolve fluvial archives in order to obtain information about past fluvial dynamics and to reconstruct palaeoenvironmental conditions, in particular in the Mediterranean Basin (e.g. Schulte 2002; Benito et al. 2003; Faust et al. 2004; Sancho et al. 2008; Silva et al. 2008; Uribelarrea & Benito 2008; Zielhofer et al. 2008, 2010; Carmona & Ruiz 2011; Houben et al. 2011). The main issues relate to the recognition of the respective role of the key factors influencing past fluvial dynamics such as climate, humans, sea-level changes, tectonics, as well as intrinsic forcing (Schumm 1973; Vandenberghhe et al. 2010).

As we know from a large number of studies on terrestrial archives (Carrión et al. 2010; Moreno et al. 2012a; Fletcher & Zielhofer 2013) the western Mediterranean underwent several marked environmental changes during the late Quaternary. Converging evidences indicate that these have been first driven by climate changes (Mayewski et al. 2004) that may relate to solar activity (e.g. Martín-Puertas et al. 2012) and melt water fluxes into the North Atlantic (Bond et al. 2001; Wanner et al. 2011). Furthermore, it is well documented that human societies affected soils and hydrological systems through deforestation and land-use activities (e.g. Faust et al. 2004; Ramos Múñoz & Pérez Rodríguez 2008; Roberts et al. 2011). Subject to uncertainties is the time-related beginning of serious anthropogenic interventions as well as their effectiveness, e.g. the potential to increase soil erosion. In this respect, the influence of Mesolithic and Neolithic cultures on landscape degradation is a lesser-known aspect, despite it has been proven that these cultures populated southwestern Spain to a greater extent (Berger & Guilaine 2009; Cortés Sánchez et al. 2012). As climate or humans have the potential to modify the environment, the question that really drives us concerns the specific reaction of landscapes to such modifications and the response times that are inherent in different geomorphologic systems.

Beside climate forcing and human impact, likewise sea-level changes and tectonic movements may also play a considerable role in triggering fluvial dynamics (e.g. Blum & Törnqvist 2000; Vis & Kasse 2009; Vandenberghhe et al. 2010). A fluctuating sea-level first means a raising or lowering of the base-level of erosion. During the Last Glacial Maximum (LGM) the sea-level in the Gulf of Cádiz was about 120 m lower than today (Lobo et al. 2002). During the subsequent transgression, until 7500 to 6500 cal. a BP (Goy et al. 1996) it rapidly rose to the Holocene highstand position. Also tectonics in the broadest sense (e.g. contribution of halokinetic deformations) may initiate fluvial aggradations by means of refilling subsiding valley sections (Benito et al. 1998; Gutiérrez et al. 2002) or, conversely, by fluvial erosion in case of tectonic uplift (e.g. Stange et al. 2012).

In this respect, the area of SW-Andalucía deserves particular attention: First, the western Mediterranean region is considered as highly sensitive to climate changes (Fletcher & Zielhofer 2013) regarding effects on hydrological, vegetation and geomorphological systems. Therefore, even slight climatic variations can cause a transition from landscape stability to activity, or conversely. This is all the more the
case as this area is particularly influenced by fluctuations of the North Atlantic Oscillation (NAO) with regard to the intensity and distribution of precipitation. At a more local scale, the Guadalete River catchment has a long population history going back to the occupation by Neanderthal populations (Finlayson 2008). Finally, the Guadalete River runs into the Atlantic Ocean and fluvial dynamics may have been strongly affected by sea-level fluctuations. Furthermore, the area is subject to significant neotectonic activity, partly related to diapirism (Maldonado & Nelson 1999). All these circumstances make the Guadalete River catchment well suited for a comprehensive study of the effects of various factors influencing Late Pleistocene and Holocene fluvial dynamics.

The overall aim of this study is to contribute to a better understanding of western Mediterranean fluvial dynamics depending on climate forcing, human activity, sea-level changes and tectonics during the Late Pleistocene and Holocene. Subordinated objectives are: i) to develop a robust stratigraphy for lower Guadalete River floodplain sediments, ii) to support stratigraphic findings by a reliable temporal resolution, and iii) to compare the results obtained for the Guadalete River with independent secondary archive studies of regional significance, i.e. pollen archives, lake records, estuarine archives, and coastal archives.

3.2 Study area

The Guadalete River catchment is a medium-sized catchment (3400 km²) situated in southwestern Spain (Figure 3.1A), between the Sierra de Grazalema to the east and the Gulf of Cádiz to the west (Figure 3.1B). The river originates in the Betic Range nearby Grazalema at 1100 m above mean sea-level (MSL) and flows 170 km until it enters the Gulf of Cádiz. The upper catchment covers parts of the Subbetic and Penibetic units of the younger folded Betic Range that are mainly composed of Jurassic to Tertiary limestone and marls, and early Miocene sandstones (Moral-Cardona et al. 1996). Here, the relief is rugged and steep covering an elevation between 300 and 1600 m MSL. Along its middle and lower valley the Guadalete River crosses the Campiña de Cádiz, a landscape characterized by gently rolling hills that mainly consist of Triassic marls, lower and middle Miocene clays and marls, and upper Miocene calcarenites and marls (Lautensach 1964; Moral-Cardona et al. 1996). One of the witnesses of Pleistocene landscape evolution is the course of the Guadalete River that leaves the Betic Range northeast of Villamartin (Figure 3.1B) and that passes the Campiña landscape with pronounced incised meanders. Díaz del Olmo (1989) suggests a sequence of five Pleistocene terraces in this area, located between 30-50 m and 3-5 m above the present floodplain. The terraces have been allocated to the Middle to Late Pleistocene, based on archeological findings (Rodríguez Vidal et al. 1993). The Holocene floodplain is incised in the youngest Pleistocene terrace and restricted to a very narrow strip along the middle river course until about 4 km east of Junta de los Ríos (Figure 3.2), where the river enters its lower course. Downstream, the floodplain enlarges up to widths ranging
between 0.5 km (in narrow sections) and 1.5 km, depending on the extent of removal of Pleistocene terraces and underlying marls by lateral erosion. The youngest Pleistocene terrace is strongly dissected but stretches along the valley margin, still with a mean elevation of 3-5 m above recent floodplain level, until Rajamanceria (i.e. about 25 km from the coastline; Figure 3.2). In this area, the meandering river has a sinuosity of 1.32. Downstream from Rajamanceria, the floodplain widens to more than 2 km and the meandering river shows a markedly higher sinuosity of 1.78. The youngest Pleistocene terrace is no longer present as Pleistocene sediments are preserved below the floodplain (see terrace crossing point in Figure 3.2). The difference in sinuosity coincides with a higher radius of meander curvature downstream of Rajamanceria. This may be linked to a reduction of the recent river gradient that averages 0.69‰ between Junta de los Ríos and Rajamanceria, and 0.17‰ between Rajamanceria and El Portal (Schumm & Lichty 1965). The study area will hence be divided into an upper section (Junta de los Ríos-Rajamanceria) and a lower section (Rajamanceria-El Portal, Figure 3.2), which will be described separately as they exhibit completely different fluvial architectures. Downstream from El Portal, the river floodplain merges with the Marismas (3 km south of El Portal, Figure 3.2), a mudflat area with an elevation of up to 3 m MSL, where sand, silt and clay was deposited in a brackish environment. The Guadalete estuary, starting at this point, reaches a width of up to 8 km. A characteristic feature of this coastal area is tectonic uplift due to the Africa-Eurasia collision that reaches a mean rate of 0.1 to 0.15 mm a⁻¹ for the last 128 ka along the Gibraltar coast 70 km south of the Guadalete estuary (Zazo et al. 1999). Further characteristics are neotectonic activities in the tectonic stress field of the Gulf of Cádiz and its hinterland that manifests itself in a multiple spread of various faults, extensive diapirism (Maldonado & Nelson 1999; Medialdea et al. 2009) and a tendency to earthquakes (e.g. Silva et al. 2005). Resultant tectonic lineation in the lower Guadalete catchment is orientated NW-SE (IGME 1984). A special feature within the Guadalete catchment is selective bulging and diapirism initiated by the increased vulnerability of Triassic and Tertiary marls to halokinetic deformation. Thus, numerous evidences are known for a small-scale diapiric uplift of up
Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

Figure 3.2. Detailed map of the study area (see Figure 3.1B) with profile sections and individual coring positions as well as cross-sections shown in Figure 3.13A. Lower and upper downstream sections are separated by the terrace crossing point of the latest Pleistocene terrace that coincides with a knick-point in the longitudinal river profile (Figure 3.13B).

to 25 m for the last 30 ka (e.g. Rodríguez Vidal et al. 1993; Gracia et al. 2008). As uplift rates exceed known tectonic uplift rates in this region (Zazo et al. 1999), a combination of tectonic compression and diapiric extrusion along major thrust faults is assumed to have taken place. An influence of tectonic/diapiric uplift on fluvial dynamics remains conceivable. For example, a ridge of Miocene and Triassic gypsum marls stretches in an arc-like manner from SE to NE that is separated from adjacent Pleistocene surfaces by its mountainous character (Figure 3.2, see also geological map in Gutierrez-Mas et al. 1996). The Laguna de Medina that evolved as a result of diapiric uplift of 20 – 25 m, is situated in the center of this ridge as well as a knick-point of the longitudinal floodplain profile (Figure 3.2 and Figure 3.13B, section La Ina). Above the knick-point we found a gradient of 0.4‰ and below, about 2 km downstream it rises to more than 0.8‰ again. Thus, the longitudinal floodplain profile of the downstream section is unbalanced, which could be caused by i) a change of the local erosion base (e.g. sea level fluctuation or meander cut-off), ii) modifications of lithological parameters or iii) by a tectonic fault that crosses the valley.

The Guadalete catchment is located in the semi-humid part of Andalucía with a typical Mediterranean climate. Rainfall vary from 646 mm a⁻¹ in Jerez de la Frontera (36°45′N/06°04′W) (Sträßer 1998) nearby the coastline to more than 2000 mm/yr in the Sierra de Grazalema (Hidalgo-Muñoz et al. 2011), with a mean annual temperature of 18°C in Jerez and about 15°C in the village of Grazalema. Characteristic for this type of climate, most of the precipitation falls between autumn and spring (winter rain climate)
when moist air is transported by westerly winds that are actually driven by the North Atlantic Oscillation (NAO; e.g. Rodrigo et al. 2000; Muñoz-Díaz & Rodrigo 2003; Trigo et al. 2004). Due to a position on the windward side of the Betic Range, areas of the Guadalete catchment receive significant amount of precipitations of which 25 to 50% are heavy rainfall. The first heavy rainstorms in autumn cause significant overland flow on the bare and dry top soils leading to severe soil erosion (Faust & Schmidt 2009). Peak discharges can reach extreme values, leading to high erosion and sedimentation processes in the Guadalete River.

Obviously, large parts of the catchment are particularly vulnerable to climate driven aridity periods and related degradation of the landscape. This becomes apparent when regarding the widespread truncation of soil profiles with already exposed parent material in the upper slope positions (Faust & Schmidt 2009). Furthermore, this indicates that intense sediment shifting due to soil erosion processes are likely to have occurred in the past. Also recent vegetation cover facilitates soil erosion processes as large parts of the catchment are used for agriculture and pasture, and Mediterranean maquis and scrubs or isolated appearances of oak forests are mainly restricted to the mountainous areas of the upper catchment.

### 3.3 Methods

**Field work:** Field surveys were conducted between 2009 and 2011 to provide sediment stratigraphy of the lower Guadalete valley. The opening of numerous gravel pits along the lower river course enabled detailed insights into the fluvial architecture of the floodplain sediments. We studied 18 exposures with partly more than 100 m in extension and a depth of up to 8 m. Furthermore, 13 percussion drillings and hand augerings were conducted up to a depth of 7 m to complement stratigraphic findings within unexcavated areas. Sedimentological and pedogenetic findings were used to differentiate between sediment units. Representative key-profiles were selected and sampled to confirm field observations and to distinguish between soils and soil sediments (reworked soil material). Therefore, 259 samples were taken for soil physical, sedimentological and geochemical analyses.

In order to detect the base of the sedimentary valley infill or even boundaries of adjacent terrace bodies, geophysical methods were applied by using electrical resistivity tomography (ERT). The eight channel multi electrode system GeoTomMK8 was used along 3 transects and 9 measurement profiles with 100 electrodes and a relevant distance of 2 m. A combination of Wenner- as well as dipole-dipole measurement technique was applied to mediate between long profile distances and the highest possible resolution. For data processing DC2DInvRes and BERT software (Günther & Rücker 2011) was used and results were visualized via ParaView software.

**Analytical work:** Several analyses were undertaken in the laboratory of the Department of Physical Geography at the Technische Universität Dresden, Germany: i) Grain-size
Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

determination was conducted by pipette analyses and wet sieve techniques (Schlichting et al. 1995) after dispersing with sodium pyrophosphate. Grain-sizes were used to differentiate sediment units, to characterize associated flow dynamics (e.g. coarser grained channel deposits vs. fine grained floodplain deposits) or to obtain indications of pedogenesis in case of steadily increasing clay contents. ii) Soil organic matter was measured via suspension and catalytic oxidation (TOC-VCPN / DIN ISO 16904). This made it possible to detect soil formation by means of enrichment of organic content in topsoil or to identify eroded and relocated topsoil material with a priori raised organic contents. iii) Carbonate content was determined by measuring the carbon dioxide gas volume after adding hydrochloric acid in a Scheibler apparatus (Schlichting et al. 1995; Zielhofer et al. 2009). This may also provide indication of soil formation in case of reduction in the upper and enrichment in the lower soil section. iv) Total iron content (Fe(t)-values) was determined after pressure digestion with concentrated nitric and hydrofluoric acid using atomic adsorption spectrometry. Pedogenic iron content (Fe(d)-values) was measured after dithionite extraction using atomic adsorption spectrometry as well (Schlichting et al. 1995). The mathematical relationship between pedogenic iron and total iron may provide information of the intensity of weathering processes in a specific sediment unit, and thus may indicate soil formation in case of an increase of values from parent material to weathering horizons (Zielhofer et al. 2009). v) Magnetic susceptibility was measured in SI units using a Bartington MS2 susceptibility meter and S2F probe (Dearing 1999) by taking the average of three measurements. There are many reasons for increased magnetic susceptibility (e.g. Baumgart et al. 2012), but we interpreted strong increases as further indication for weathering processes, or soil formation (resp. relocated soil sediment) (Zielhofer et al. 2009). vi) The tree genus of each wood sample was microbiologically identified based on species-specific anatomical features using a stereo microscope with reflected and transmitted light functions and a resolution of up to 500 times (Schweingruber 1990) in order to gain possible information on related palaeoenvironmental conditions.

Radiocarbon dating: To assess a temporal resolution of sedimentation and soil formation periods, radiocarbon dating was carried out on 29 samples of insitu and reworked charcoal, wood, organic sediment, and 5 samples of shell fragments (Tab. 1). Samples for dating were taken from bottom or top of a sediment unit to identify onset or offset of sedimentation, or in form of bulk samples from buried topsoil horizons in order to identify the latest time for humic acid formation. The measurements were performed by the AMS $^{14}$C laboratories in Kiel and Erlangen, Germany, and Miami (Beta, United States), and all $^{14}$C ages were calibrated using CALIB 6.0 (Stuiver & Reimer 1993) with the IntCaL09.14c calibration curve (Reimer et al. 2009). The mean of the 2σ probability interval is denoted in Table 3.1. All data belonging to radiocarbon dating of consulted studies in the interpretation chapter were likewise calibrated as above to ensure comparability.

The procedure of radiocarbon dating of calcium carbonate from terrestrial mollusk shells is still controversial (Goodfriend et al. 1999; Innocent et al. 2005;
Magnani et al. 2007). Due to the tendency to incorporate old organic or inorganic carbon, certain fractionation processes of the carbon isotopes may lead to age overestimation. However, due to the absence of alternative sample material for radiocarbon dating, five samples of shell fragments from the La Ina cross section were used to unveil important sedimentation periods. Taking account for its poor conservation status the determination of the species was infeasible. However, as the ages are absolutely consistent with ages obtained from different carbon dating samples, we included the shell dating as reliable age estimation of the respective sedimentation periods (Pigati et al. 2010).

Table 3.1 Radiocarbon dates from the lower Guadalete River valley.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Lab no.</th>
<th>Material</th>
<th>Δ^13C age yrs BP</th>
<th>Cal. age BP (2σ)</th>
<th>Significance</th>
<th>Sed. unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braza-II</td>
<td>Beta-29518</td>
<td>Trunk (Fraxinus sp.)</td>
<td>4050±40</td>
<td>4699±188</td>
<td>Start sedimentation</td>
<td>SU-9a</td>
</tr>
<tr>
<td>Braza-I</td>
<td>Erl-15179</td>
<td>In situ macrofossil (Arecaceae)</td>
<td>3936±36</td>
<td>4381±133</td>
<td>Stability</td>
<td>SU-9a</td>
</tr>
<tr>
<td>Braza-III</td>
<td>KIA 39216</td>
<td>In situ macrofossil (Arecaceae)</td>
<td>3840±30</td>
<td>4279±128</td>
<td>Stability</td>
<td>SU-9a</td>
</tr>
<tr>
<td>Braza-II</td>
<td>Beta-293517</td>
<td>In situ macrofossil (Arecaceae)</td>
<td>320±40</td>
<td>391±89</td>
<td>Channel aggradation</td>
<td>SU-13a</td>
</tr>
<tr>
<td>Braza-I</td>
<td>Erl-15178</td>
<td>Ex situ charcoal</td>
<td>313±39</td>
<td>387±89</td>
<td>Active sedimentation</td>
<td>SU-13b</td>
</tr>
<tr>
<td>Braza-III</td>
<td>KIA 39215</td>
<td>Ex situ charcoal</td>
<td>170±25</td>
<td>143±143</td>
<td>Start sedimentation</td>
<td>SU-14</td>
</tr>
<tr>
<td>Braza-I</td>
<td>Erl-15180</td>
<td>Ex situ charcoal</td>
<td>122±38</td>
<td>137±137</td>
<td>Active sedimentation</td>
<td>SU-14</td>
</tr>
<tr>
<td>El Torno</td>
<td>KIA 39191</td>
<td>Ex situ charcoal</td>
<td>1140±65</td>
<td>1082±152</td>
<td>Channel aggradation</td>
<td>SU-13b</td>
</tr>
<tr>
<td>El Torno</td>
<td>KIA 39194</td>
<td>Ex situ charcoal</td>
<td>1140±65</td>
<td>1082±152</td>
<td>Channel aggradation</td>
<td>SU-13b</td>
</tr>
<tr>
<td>El Torno</td>
<td>KIA 39193</td>
<td>Ex situ charcoal</td>
<td>1075±25</td>
<td>993±61</td>
<td>Active sedimentation</td>
<td>SU-11b</td>
</tr>
<tr>
<td>MEDINA-3</td>
<td>Beta-294976</td>
<td>Organic sediment</td>
<td>7190±40</td>
<td>8046±108</td>
<td>End soil formation</td>
<td>SU-5b</td>
</tr>
<tr>
<td>INA-3</td>
<td>Beta-294975</td>
<td>Shell (meollusk)</td>
<td>7020±40</td>
<td>7851±93</td>
<td>Start sedimentation</td>
<td>SU-6</td>
</tr>
<tr>
<td>INA-1</td>
<td>Beta-321543</td>
<td>Shell</td>
<td>5230±30</td>
<td>6045±129</td>
<td>Start sedimentation</td>
<td>SU-8</td>
</tr>
<tr>
<td>INA-3</td>
<td>Beta-300819</td>
<td>Shell</td>
<td>4850±30</td>
<td>5568±83</td>
<td>Start soil formation</td>
<td>SU-8</td>
</tr>
<tr>
<td>INA-1</td>
<td>Beta-300821</td>
<td>Shell</td>
<td>4460±30</td>
<td>5128±158</td>
<td>Start soil formation</td>
<td>SU-8</td>
</tr>
<tr>
<td>INA-1</td>
<td>Beta-321544</td>
<td>Shell</td>
<td>3520±30</td>
<td>3788±87</td>
<td>Start soil formation</td>
<td>SU-9a</td>
</tr>
<tr>
<td>José Antonio</td>
<td>KIA 39207</td>
<td>In situ macrofossil (Arecaceae)</td>
<td>911±28</td>
<td>830±86</td>
<td>Stability</td>
<td>SU-11a</td>
</tr>
<tr>
<td>José Antonio</td>
<td>Erl-15176</td>
<td>Ex situ charcoal</td>
<td>542±40</td>
<td>576±66</td>
<td>Start sedimentation</td>
<td>SU-12</td>
</tr>
<tr>
<td>José Antonio</td>
<td>Erl-15175</td>
<td>Ex situ charcoal</td>
<td>510±35</td>
<td>564±61</td>
<td>Active sedimentation</td>
<td>SU-15</td>
</tr>
<tr>
<td>José Antonio</td>
<td>Erl-15174</td>
<td>Ex situ charcoal</td>
<td>348±39</td>
<td>402±90</td>
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<td>SU-13b</td>
</tr>
<tr>
<td>La Barca</td>
<td>Erl-15156</td>
<td>Ex situ charcoal</td>
<td>343±37</td>
<td>398±89</td>
<td>Active sedimentation</td>
<td>SU-13b</td>
</tr>
<tr>
<td>La Barca</td>
<td>Erl-15158</td>
<td>Ex situ charcoal</td>
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<td>396±86</td>
<td>Active sedimentation</td>
<td>SU-13b</td>
</tr>
<tr>
<td>Pozo Romano</td>
<td>Erl-15182</td>
<td>Ex situ charcoal</td>
<td>11,309±178</td>
<td>13,718±385</td>
<td>Active channel filling</td>
<td>SU-3</td>
</tr>
<tr>
<td>Pozo Romano</td>
<td>Erl-15181</td>
<td>Soot particle from fire ground</td>
<td>2234±35</td>
<td>2245±93</td>
<td>Start colluviation</td>
<td>SU-10</td>
</tr>
<tr>
<td>Pozo Romano</td>
<td>Beta-294966</td>
<td>In situ macrofossil (Tamarix sp.)</td>
<td>150±30</td>
<td>141±141</td>
<td>SU-1</td>
<td></td>
</tr>
<tr>
<td>Rancho Romero</td>
<td>KIA 39213</td>
<td>Organic sediment</td>
<td>5436±41</td>
<td>6216±90</td>
<td>Active sedimentation</td>
<td>SU-9c</td>
</tr>
<tr>
<td>Rancho Romero</td>
<td>KIA 39214</td>
<td>Ex situ charcoal</td>
<td>3975±30</td>
<td>4414±111</td>
<td>Active sedimentation</td>
<td>SU-9b</td>
</tr>
<tr>
<td>Rancho Romero</td>
<td>KIA 39212</td>
<td>Ex situ charcoal</td>
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<td>SU-9b</td>
</tr>
<tr>
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<td>KIA 39213</td>
<td>Humic acid</td>
<td>3843±29</td>
<td>4279±126</td>
<td>SU-9c</td>
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<tr>
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<td>Erl-15177</td>
<td>Ex situ charcoal</td>
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<td>Start soil formation</td>
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</tr>
<tr>
<td>Spinola</td>
<td>KIA 23951</td>
<td>In situ firesite</td>
<td>8205±48</td>
<td>9159±143</td>
<td>Soil formation</td>
<td>SU-5b</td>
</tr>
<tr>
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<td>KIA 23950</td>
<td>Ex situ charcoal</td>
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<td>1969±72</td>
<td>Active sedimentation</td>
<td>SU-10</td>
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</tbody>
</table>
3.4 Stratigraphic findings and sedimentation patterns within the Guadalete valley

The valley of the lower Guadalete River shows a fluvial architecture that is complex and inconsistent along specific river sections. According to stratigraphic findings, the lower reach of the Guadalete River can be divided into two sedimentary areas – the upper downstream section at a distance between 50 and 25 km from the coastline, between Junta de los Ríos and Rajamancera, and the lower downstream section close to the estuary reaching from Rajamancera in a distance of 25 km from the coastline to the recent coastline itself (Figure 3.2). This distinction is first visible in present-day meander geometry. In addition, these river sections are characterized by strongly diverging sedimentation and erosion dynamics.

3.4.1 Upper downstream section (Junta de los Ríos - Rajamancera reach)

This river section is characterized by a juxtaposition of several sedimentary bodies and refers to highly dynamic sedimentation conditions, which are expressed in terms of alternating periods of sediment deposition and erosion. As mentioned above, the river valley of this section is structured by a series of valley widening and narrow sections (Figure 3.2). Along the latter, the river typically tends to repeatedly accumulate and remove sediments. In contrast, sediment bodies are more preserved in distal floodplain positions in areas of valley widening. Three main sedimentary successions can be identified that become increasingly younger from distal to proximal floodplain positions. Starting with a Late Pleistocene sedimentary body in distal positions, this is followed by a sequence of mid-Holocene sediments in more proximal positions and a late Holocene sequence nearby the recent river course. The general stratigraphic configuration of this river section points to gravels at the base of the sequences, followed by more or less sandy material that is finally topped by flood loams.

3.4.1.1 Late Pleistocene sediments

A mostly continuous sediment body that is assumed to be of Late Pleistocene age stretches mainly along the right bank of the Guadalete River, between around 3 and 5 m above the present floodplain (Figure 3.2). Generally, it is separated from the Holocene floodplain by the river channel or river branches. On the left bank of the Guadalete River, this terrace body is only preserved where the valley widens (Figure 3.2), and the differentiation from the recent floodplain level is difficult due to the presence of flood loam and slope deposit cover. In the studied sections, the associated succession is about 4 m thick and is found above grayish to whitish Triassic and Tertiary marls. The Pozo Romano profile (Figure 3.3) is typical for this succession. It is characterized by a gravel
Figure 3.3. Late Pleistocene succession of the profile section ‘Pozo Romano’ (36°36′42″N, 5°57′26″W) with units SU-1 to SU-3. This profile is documented in a section extending NW to SE and NE to SW (middle to right side of upper panel with continuation in the lower panel). For results of wood anatomical analyses and radiocarbon dating see Figure 3.5 and Table 3.1.
body that is assigned to sediment unit 1 (SU-1). It shows a poor grain sorting of the gravels and a predominant embedding of gravels into a sandy to loamy matrix. SU-1 exhibits horizontal stratification of coarse- and fine-grained gravel layers with interbedded sand layers of up to 1 m thickness. Gravels are strongly cemented with calcium carbonate, and pebbles show several mm thick efflorescence (carbonate coatings) at the bottom side. Travertine or caliche fragments with diameters of up to 1 m that are afflicted with scour holes occur occasionally on the boundary between gravels and the underlying marls (Figure 3.3). Gravels do not show preferential orientation, and a uniform deposition in braided channels seems likely.

Strong weathering and rubefication affected the upper part of the terrace consisting of sand and gravels (SU-2). Fe(d)/Fe(t) ratios of 0.49 were measured within this rubefied soil horizon, which is far beyond values measured in other units. Settlement pits of late Phoenician or possibly early Roman age (2245±93 cal. a BP in Figure 3.3) that have directly been inset into the soil material provide evidence for exposure duration of at least several thousand years. In the northwestern part of the Pozo Romano profile, a channel incised during the latest Pleistocene around 30 m wide and 3.5 m deep that can be horizontally followed several hundred meters along the terrace surface. The radiocarbon dating of a charcoal fragment yielded an age of 13718±385 cal. a BP, indicating that the filling of this channel occurred during the Bølling and Allerød interstadials (Figure 3.3, Table 3.1). Inside the sandy channel filling (SU-3) a dark humic topsoil horizon has developed turning into white precipitates of bog lime in its lower part. The whole section is covered with blackish colluvial sediments that contain plenty of brick and pottery fragments (SU-10). According to the radiocarbon age of 2245±93 cal. a BP that was derived from soot particles of a buried fire ground (Figure 3.3, Table 3.1), slope deposition took place during latest Phoenician and Roman times. A bricked well in the southwestern part of the section was built in a cavity filled with water between the impermeable marls and the gravel layer. In the northeastern part, within gravels of SU-1 an injection of whitish marl presumably due to plastic flow is shown. Macro-botanical analyses carried out on wood samples out of this injection resulted in the occurrence of tamarisks (Tamarix sp.) (Figure 3.5). A radiocarbon age of 140 cal. a BP was derived from one of these wood samples (Tab. 3.1), indicating recent contamination by roots.

3.4.1.2 Mid-Holocene sediments (5000 - 2000 cal. a BP)

The field observations indicate that mid-Holocene sedimentation took place after a strong incision and erosion of late Pleistocene sediments. No older Holocene sediments were found, even in distal floodplain positions. Time and duration of incision are unknown, but the erosion surface of the marls at the base of the mid-Holocene sediments is about 5 m lower than the Late Pleistocene erosion surface. The mid-Holocene succession is typically divided into two parts, a lower part composed of coarse gravels (SU-9a) and an upper part composed of sand and loamy material
3. Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

Figure 3.4. Mid- to late Holocene succession of the profile ‘Braza-II’ (36°36′46″N, 5°56′58″W) located in a proximal floodplain position. Results of macrobotanical analyses (yellow circles) are shown in Figure 3.5.
Figure 3.5. Identified tree species in absolute numbers of samples from profile ‘Pozo Romano’ and ‘Braza-II’ (Figure 3.4).

(SU-9b). The gravels can be differentiated into specific units. At the base of the Braza-II profile nearby Torrecera (Figure 3.4), directly above the grayish marls, a gravel layer about 1 m thick refers to dense gravel bedding with intercalated sand and clay lenses. These lenses include numerous trunk fragments (Figure 3.5), in particular of cork oaks (*Quercus suber* L.). The dating of a cork oak yielded a radiocarbon age of 4609±188 cal. a BP (Table 3.1). This age is considered as the beginning of the deposition of the upper 3 m of gravels (SU-9a) with a homogenous horizontally layered structure. Gravels are unsorted and have a sandy matrix. In the uppermost part several rootstocks of palm trees (*Arecaceae sp.*) appear, wrapped in grayish clay and floating in the gravel. The age of the end of this sedimentation period is uncertain, but we assume that the deposition of SU-9a should have lasted less than 300 years (Figures 3.8B, 3.10A). A distinct erosion unconformity cuts this gravel layer, which is covered by younger gravels. Similar conditions can be found in the Braza-I profile, a few hundred meters downstream, where a rootstock of a palm tree in a depth of 7 m yielded a radiocarbon age of 4381±133 cal. a BP (Figure 3.6E, Table 3.1). Gravels of SU-9a are likewise visible about 12 km upstream of Torrecera, which is shown by ERT-measurement (Figure 3.7A) conducted parallel to the JA-drilling section south of Junta de los Ríos (Figure 3.2). Two hypotheses may be proposed to explain the irregular basal surface of the underlying marls. First, it might indicate the erosive surface prior to aggradations of SU-9a gravels. Second, the undulating surface might appear distorted.
Figure 3.6. Compilation of profile sections (see locations in Figure 3.2). A. Section ‘El Torno-III’ (36°36'23"N, 5°57'34"W). B. ‘Spinola’ profile (36°37'03"N, 5°58'52"W) situated 3 km upstream of the terrace crossing point. C. Refilled channel of the ‘Rancho Romero-II’ section (36°40'40"N, 5°52'34"W) about 200 m NE of ‘Rancho Romero-I’ section (Figure 3.8). D. Section ‘El Torno-I’ (36°36'11"N, 5°57'44"W) that documents ongoing channel aggradations in a proximal floodplain position followed by channel incision and refilling. E. Section ‘Braza-I’ (36°36'40"N, 5°57'00"W) situated 200 m SW of section ‘Braza-II’ (Figure 3.4).
Figure 3.7. A. Elevation profile of the cross-section ‘Junta de los Rios’ (see Figure 3.13A) and results of ERT measurements of the southern side conducted parallel to the coring transect of the JA section. Resistivity is extremely low due to the high concentration of salts originating from Triassic and Tertiary marls. Therefore, measured resistivity exceeding a value of 20 Ohm-m corresponds to gravel. Coarse grained material and gravel at the base of coring JA-2, JA-3 and JA-5 (see Figure 3.10A) confirm this interpretation. Two missing electrodes corresponding to the width of the road account for the deflection of the gravel body near the road (360 m). B. Most proximal segment of the ERT section measured in north–south direction parallel to the La Ina section (lower downstream section, see Figure 3.2). A gravel layer is visible between 9 and 15 m below surface level (70 to 140 m) and corresponds to SU-13a or SU-4. Not shown is the continuation of the ERT section that reaches 150 m further to the south indicating another incipient gravel layer at depths between 9 and 16 m below ground level (SU-4).

due to disturbances of the ERT-signal. Saturation by a very saline water body that is recruited from surrounding gypsum marls may increase the conductivity significantly, especially in depths below 10 m, which leads to a blurring of the transition of gravels to marls.

The succession SU-9b following above mainly consists of sands at the base with predominantly fine sands in the upper part (Rancho Romero profile, Figure 3.8A, B). This fining-upwards trend provides strong indications of hydromorphic overprint. In the upper range of SU-9b a strong soil formation is expressed by considerable pedogenic clay enrichment as well as a reddish brown color. Despite an increasing total iron content (Fe(t)), the significant increase of Fe(d)/Fe(t)-ratios reveals enhanced iron activity that gives further evidence for pedogenesis. The radiocarbon dating of a charcoal fragment at the lower boundary of the soil and of a charcoal layer at the bottom of SU-9b yielded ages of 4414±111 and 4335±87 cal. a BP, respectively (Table 3.1). Therefore, sedimentation of SU-9b is assumed to have occurred in a short time-span. High values for organic content in the lower part of SU-9b could be indicative for soil sediment. The above unit SU-9c is mainly composed of dark-brown loam. It is characterized by high Fe(t) and Fe(d) values (Figure 3.8B). Since no pedogenetic features could be proved by analytics for the lower and middle part, SU-9c is assumed
to consist of soil sediment. Only the uppermost part bears pedogenetic indications (increase of organic content and Fe(d)/Fe(t)-ratio, highly aggregated soil structure). The radiocarbon dating of organic material in this soil yielded an age of 6216±90 cal. a BP.
3  Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

(Figure 3.8B, Table 3.1). This result suggests an incorporation of old carbon maybe from former soil formation, and thus provides further evidence for this material to be composed of soil sediments. In another part of the Rancho Romero profile (Figure 6C), the contact between SU-9b and the upper unit SU-10 is clearly erosive, and medium-grained gravels have been found just above the erosion surface, indicating a highly dynamic onset of sedimentation. The overlying sediments of SU-10 show higher values for organic, clay and iron contents and were assigned to a more recent sedimentation period. Similar sediment characteristics have been recognized in the Spinola section located west of El Torno. The radiocarbon dating in the upper part of this unit SU-10 yielded an age of 1969±72 cal. a BP (Figure 3.6B).

3.4.1.3  Late Holocene sediments (<2000 cal. a BP)

A change of fluvial dynamics took place during the Medieval period and becomes evident in form of a network of several up to 80 m wide meandering channels that are incised about 3 m into older sediments, with a clear erosive surface (Figures 3.6C, D, and 3.8A). These channels extend with wide loops even across distal floodplain positions and can be easily recognized as the blackish infill sharply contrasts with the grayish and pale floodplain surface. Sediment filling (SU-11b) shows high organic and clay contents (Figure 3.8A). Sediments are layered and alternate between clay-rich dark and humic substrates with blocky structure, and very fine laminated grayish to whitish marl sediments. Occasionally, these sediments are rich in mollusks and ceramics (Figure 3.6C, D). The absence of coarse grained channel deposits indicates that the floodplain channels have not been used by the main river, and thus can be seen as secondary channels. In the main river channel of this time, at a depth of approximately 3.8 m, a rootstock of an apparently insitu palm tree yielded a radiocarbon age of 830±86 cal. a BP (José Antonio profile, Figure 3.9C). Together with a well-defined layer of grayish clay within the same stratigraphic position, this points to temporary stability. Possibly, this former surface marks the base level for the incision of the secondary channels. The time of system change from channel incision to channel filling is indicated by charcoal layers at the base of a channel that yielded radiocarbon ages of 993±61 and 848±81 cal. a BP (Figures 3.6D, 3.8A; Table 3.1). At least 2 refilled channels are shown in the JA-section (Figure 3.7A, ERT-section: 460 to 490 m and 560 to 600 m). Lowest resistivity values (<10 Ohm-m) point to high clay contents (cf. detailed section in Figure 3.8A) inside these channels. However, in such settings ERT-measurements are not suitable for precise field surveys as high salinity with associated lowest resistivity values do not allow further stratigraphic differentiations of fine-grained fluvial sediments. In the main river channel, gravels (SU-11a) were deposited after 830±86 cal. a BP and sands accumulated after 576±66 cal. a BP (SU-12) (José Antonio profile, Figure 3.9C). Exceptionally strong sedimentation was found during the Little Ice Age (LIA) period. Corresponding sediments occur nearly ubiquitous in
Figure 3.9. Sediment successions and analytical data. A. Profile ‘La Barca’ (36°38′23″N, 5°55′32″W). B. Profile ‘Torrecera’ (36°36′25″N, 5°57′02″W). C. Profile ‘José Antonio’ (36°40′33″N, 5°52′50″W). All profiles share a common strong sedimentation of alternating sandy and clayey layers at 0.4 cal. ka BP. For legend see Figures 3.6 and 3.12.
proximal positions along the river course. Older sediments were cleared-out over a width of 300 to 800 m before this area was rapidly filled up with younger sediments (SU-13a, SU-13b, SU-14, and SU-15) during the last 400 years. Generally, these youngest sediments overlie a distinct erosion discordance at the base. In the lower part, the sediments are dominated by gravels (SU-13a) that show a cross-bedding structure and a lateral growth direction (e.g. towards northwest in the Braza-II profile, Figure 3.4). According to the large lateral extension of these deposits, strong dynamics of the meandering river channel is expected for this period with the potential to cut deeply into older channel bed deposits and to build up several meters of clast-supported sediments. In the Braza-II profile a radiocarbon dating within the upper gravels yielded a depositional age of 391±89 cal. a BP (Figure 3.4). The upper part is dominated by fine sediments. Field observations and radiocarbon dating in several profile sections (profiles La Barca, Figure 3.9A; José Antonio, Figure 3.9C and Braza-I, Figure 3.6E; see also profiles Braza-II, Figure 3.4; El Torno-III, Figure 3.6A and Torrecerra, Figure 3.9B) indicate a thick sediment accumulation in a short time-span at around 400 cal. a BP in proximal locations. Sediments are often fine laminated (SU-13b) and show a thickness of around 3 m with alternating layers of ochre to pale gray sandy material and dark brown-grey material containing a high proportion of clay (up to 40%) and organic matter (partly more than 0.75%). Thin silty layers are intercalated, suggesting laminar washing processes on the former surface (e.g. profile Torrecerra, Figure 3.9B). They may be related to burnt layers of soot and charcoal particles. The color and the high organic content indicate that the material mainly originates from eroded top-soils of the marls of the Campiña de Cadiz. As shown in the profile Braza-I (Figure 3.6E), the sediments of SU-13b were partly cleared-out after the LIA, prior to a new accumulation of laminated marl sediments (SU-14). A precise age determination for this evolution is difficult due to calibration uncertainties.

3.4.1.4 Composite profile

Taking all shown sediment units into account, a composite profile has been generated (Figure 3.10A). Large parts of the floodplain are dominated by a Late Pleistocene terrace body (SU-1) that rises about 2 m above the recent floodplain level. Individual channel fillings (SU-3) indicate that the decoupling of the terrace from active river processes did not occur before the Younger Dryas. After a strong incision and clearing-out, mid-Holocene sediments (SU-9a, SU-9b) have been deposited above a distinct erosion discordance, leading over to another period of soil formation and strong river meandering after about 4300 cal. a BP. Since 2200 cal. a BP, intense floodplain sedimentation (SU-10) took place, which may be related to slope erosion on the Late Pleistocene terrace. Channel incision even in distal floodplain positions occurred until 830 cal. a BP, before the deposition of dark humic material (SU-11b) originating from the Campiña de Cadiz marls. A last strong dynamic impulse is visible during the LIA with intense river erosion and a subsequent refilling with marl sediments (SU-13b, SU-14).
Figure 3.10. A. Composite profile of the upper downstream section including most important $^{14}$C dating results. B. Composite profile of the lower downstream section combining the results of the coring transects ‘La Ina’ and ‘Medina’.
3.4.2 Lower downstream section close to the estuary (Rajamancera - coastline reach)

The lower part of the study area shows completely different sedimentation and sediment preservation patterns. After the river crosses a N-S stretching ridge of Triassic marls (Figure 3.2) which is probably related to diapirism or tectonic uplift, the valley widens up to more than 2 km (Figure 3.2), enabling a better preservation of sediments from erosion. Except for the Pleistocene terrace gravels preserved on top of meander-mountains (isolated hills formed by meander down cutting), no Pleistocene or Holocene terraces were found close to the floodplain.

Due to the lack of outcrops, stratigraphic work is based on four percussion drillings and four hand augerings that were carried out in the area of an abandoned meander (but which may still be flooded during annual high-floods) located in the vicinity of the Laguna de Medina (Figures 3.2, 3.10B). DrillingsINA-1 to INA-5 are located in the active floodplain close to the present-day river, while drillings MEDINA-2 and MEDINA-3 are located inside the abandoned meander. MEDINA-1 is located at the edge of the active floodplain, at the transition to the meander.

3.4.2.1 Early Holocene sediments (~10000 - 8000 cal. a BP)

As drilling has been restricted to a depth of 7 m due to technical reasons, none of the drillings was able to reach the base of the Holocene sediment body. ERT-measurements revealed that the basal Holocene sediments are composed of gravels (SU-4) that were buried at a depth between 9 and 15 m below ground level (Figure 3.7B). This observation is consistent with the description of a borehole located on a farmstead in the vicinity of the drilling area. Sands (SU-5a) and sandy loams (SU-5b) that cover the lowermost gravel unit show intense hydromorphic features and low contents of organic matter. The upper part of this unit (between 3 and 4 m below ground level) shows intense soil formation (profiles INA-3 and MEDINA-1, Figures 3.11B, 3.12A). This is clearly indicated by the red-brown color, the pedogenic clay enrichment (38 - 50%), the total iron content (40 g kg⁻¹) and high Fe(d)/Fe(t)-ratio (0.37), as well as the high magnetic susceptibility values (between 40 and 50 SI·10⁻⁵ m³ kg⁻¹). In the lower part and especially below the subsoil horizon, carbonate concretions up to 1 cm thick have been formed (Figures 3.11B, 3.12A). Radiocarbon dating of an organic sediment sample taken from the black-brown topsoil horizon suggests that pedogenesis took place until 8046±108 cal. a BP (Figure 3.12B, Table 3.1). This surface level was affected by erosion, which resulted in an inconsistent and partly truncated soil surface (Figure 3.10B).

This result is consistent with observations conducted in profile Spinola, which is located close to the transition from the upper to lower downstream section (Figure 3.6B). Above gravels that were linked to SU-4, a well-developed soil in sandy flood loam (SU-5b) actually yielded a radiocarbon age of 9159±143 cal. a BP.
Figure 3.11. Profile descriptions and analytical data of drillings along the La Ina section. A. Profile INA-1 (36°38′19″N, 6°1′56″W). B. Profile INA-3 (36°38′50″N, 6°02′16″W). C. Profile INA-5 (36°39′05″N, 6°02′17″W). Profiles are shown and contextualized in Figure 3.10B. For legend see Figures 3.6 and 3.12.
3.4.2.2 Mid- to late-Holocene sediments (<8000 cal. a BP)

Clayey to sandy loams are the typical sediments that accumulated during the mid-Holocene. In the active floodplain, three sediment units (SU-6, SU-8, and SU-9c) have accumulated after soil formation stopped in SU-5b (Figure 3.12B, Table 3.1). A coarsening-upward succession within SU-6 (Figure 3.11B) and SU-8 (Figure 3.11A) may indicate either increasing dynamics on the floodplain or changing distances to the
main river channel. According to radiocarbon dating of shell fragments, the first sedimentation period (SU-6) started at about 7851±93 cal. a BP (profile INA-3, Figure 3.11B) and lasted until 6045±129 cal. a BP, before a pronounced soil formation (profile INA-1, Figure 3.11A). Sediments of the following unit (SU-8) show high contents of clay and organic carbon, and a maximum in magnetic susceptibility in the lower part, which indicates SU-8 as being soil sediment (eroded and relocated soil material) (Figure 3.11A). Sedimentation of SU-8 lasted until 5568±83 cal. a BP (profile INA-3, Figure 3.11B) or 5128±158 cal. a BP (profile INA-1, Figure 3.11A), before a further stability period including soil formation. This stability period was replaced by the accumulation of units SU-9b and SU-9c that show high content of clay and organic matter even within the lower parts, and thus are likewise considered as soil sediments. A radiocarbon age in profile INA-1 indicates the end of sedimentation of SU-9c at about 3788±87 cal. a BP (Figure 3.11A, Table 3.1).

South of the active floodplain and the meander-mountain, coring MEDINA-1, MEDINA-2 and MEDINA-3 have been drilled within the area of a palaeo-meander (Figure 3.10B). Here, a sequence of nearly 7 m of clayey material (SU-7) accumulated above the strong soil developed in SU-5b. These clayey sediments are hardly differentiable. Only a slightly darker phase between 280 and 350 cm below ground level in profile MEDINA-3 point to soil formation under stable conditions, which is confirmed by analytical work (Figure 3.12B). Thus, it must be assumed that the river meander has been abandoned before the sedimentation of sandy loams (SU-6) in the active floodplain. The clayey sediments of SU-7 indicate a frequent flooding during high-flood events with the accumulation of just finest material during still-water conditions. Apparently, sedimentation of SU-7 ranged over a long time span, simultaneously with the sedimentation of SU-6, SU-8 and SU-9b/c in the active floodplain.

A highly dynamic period is indicated for latest Holocene times. In proximal as well as in more distal positions, refilled channels were found that incised several meters into the floodplain level (Figure 3.10B, profiles INA-2 and INA-5 and Figure 3.7B). Sediments are composed of sandy loams that alternate with clayey and humic layers in the upper part. These features, in combination with brick fragments in profile INA-5 (Figure 3.11C) led to the assumption that these channel fills may be correlated with the latest Holocene sediments of SU-13 that were detected in the upper downstream section. Comparable sandy sediments have been found in profile MEDINA-1. Due to its position at the edge of the abandoned river meander (Figure 3.2), there is no evidence that the river was running through the river meander during that time. The uppermost sediment unit with a ubiquitous distribution along the drilling transect consists of clayey material rich in organic content with pale brown-grey colors belonging to the most recent deposition (SU-15). For example, a high-flood event lasting several days in March 2010 produced a flood loam cover approximately 10 cm thick even in most distal floodplain positions.
3.5 Interpretation – Floodplain evolution and the influencing factors

Determining impact of sea level changes on fluvial dynamics is primarily observable for the Late Pleistocene when sea level fluctuations reached values of up to 120 m. In the course of the postglacial sea level rise, apparently other parameters started to play a decisive role as no clear evidence was found for a Holocene control of the fluvial system by sea level changes. Tectonic or diapiric uplift may have had the potential to influence floodplain gradients and related fluvial sedimentation patterns, but there are no clear signs of a tectonic forcing of the Holocene floodplain dynamics. Therefore, the Holocene fluvial dynamics and especially the onset and offset of sedimentation periods are primarily interpreted in terms of environmental conditions and anthropogenic forcing.

3.5.1 Stages of floodplain evolution

3.5.1.1 Late Pleistocene dynamics (SU-1 to SU-3)

The oldest indication of fluvial dynamics in this study is provided by a Late Pleistocene terrace mainly composed of gravels (SU-1). At Rajamancera, the terrace surface disappears and the terrace sediments are found below the recent floodplain level (indicated by the terrace crossing in Figure 3.2). The depositional age of SU-1 remains unknown. Possible indications arise from the studies carried out in the Guadalete River estuary just in front of the recent coastline, by Dabrio et al. (2000), who documented fluvial gravels in a depth more than 30-35 m below present sea level. These gravels are up to 10 m thick and the authors assume a depositional age around 30/35 cal. ka BP, based on radiocarbon dating. According to the current data situation, terrace gravels of SU-1 are correlated with these gravels found by Dabrio et al. (2000), and thus deposition of SU-1 is assumed to have taken place during MIS 3, prior to the strongest sea level drop of the LGM. This timeframe of aggradation is consistent with other Spanish rivers such as the Tajo (Cunha et al. 2012) or the Jarama (Wolf et al. 2013). The reconstructed gradient of the gravel body (SU-1) is visible in Figure 3.13B and shows a steepening of the gradient at about 25 km from the coastline, in response to the lower sea level.

During the LGM, with an estimated sea level drop of about 120 m (Hernández-Molina et al. 1994; Lobo et al. 2002) in the Gulf of Cádiz, the fluvial channel of the Guadalete incised into the coastal plain that likewise affected the lower Guadalete Valley in form of increased river erosion. Based on the shape of the valley, it is assumed that substantial river erosion has taken place with a spatial extension up to Rajamancera, as downstream of Rajamancera the valley broadens out (Figure 3.2), indicating strong lateral erosion. Furthermore, extensive fluvial incision is documented for the upper downstream section with erosion depths of more than 7 m (Figure 3.10A) that resulted in the morphological formation of the terrace (SU-1/SU-2). It is likely that
Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

Figure 3.13. A. Compilation of cross-sections taken from a digital terrain model. All cross-sections are shown in Figures 3.2 and 3.13B. LP = Late Pleistocene terrace; H = Holocene floodplain level; H(E) = Holocene floodplain level partly excavated due to gravel quarrying. B. Longitudinal profile of the recent floodplain level showing the lowermost Guadalete River section at a distance of 50 km to the coastline. Delineated are (1) the recent river level (blue), (2) the Holocene erosion surface as the base of Holocene sediments (green), (3) the surface and the base of the Late Pleistocene gravels of SU-1 (red). Surface lines are based on measuring points that were taken from the digital terrain model or from the studied profile sections. Depths near the coastline are taken from Dabrio et al. (2000), although the base of the Late Pleistocene gravels was not encountered during coring and thus is uncertain. Dashed lines represent estimations based on the drilling within the estuary (Dabrio et al. 2000). The terrace crossing point, where the Late Pleistocene terrace (SU-1) descends below the recent floodplain level coincides with a strong increase of the Late Pleistocene terrace’s gradient. C. Longitudinal profile of the entire Guadalete River with position of the detailed section shown in Figure 3.13B. The three steps within the profile illustrate the position of water reservoirs.

The reworked material passed through the estuary as no corresponding deposits were found by Dabrio et al. (2000). In the Pozo Romano section, a channel has incised up to a depth of 3-4 m (Figure 3.3) into SU-1 and SU-2. This erosion, which occurred before 13718±385 cal. a BP, is likely to be linked to the incision in the main river channel (Figure 3.14).

Furthermore, Dias et al. (2000) found that rivers in Portugal showed higher discharges caused by longer wet seasons and spring ice melting during the LGM. This observation fits well with our suggestion of intense clear-out of floodplain sediments.
during LGM. Combined with the vicinity of the sea, this may explain that in contrast with several other rivers in Spain (Macklin et al. 2002; Schulte 2002; Wolf et al. 2013), the MIS 2 sediments have not been found in the Guadalete River valley.

The channel was then filled with about 1.5 m of sandy fluvial sediments (SU-3) during the Bølling and Allerød interstadials. Thus, it seems that the Late Pleistocene terrace body was decoupled from active river processes after the Allerød interstadial (~13.7 cal. ka BP), possibly due to continued river incision during the Younger Dryas (see Figure 3.14). Formation of the blackish floodplain soil started in the channel fill after 13.7 cal. ka BP during Bølling and Allerød interstadials. This can be linked to the moist and temperate conditions, which are reported e.g. by Pons & Reille (1988), Fletcher et al. (2007) (Figure 3.14) and Zazo et al. (2008).

3.5.1.2 Early Holocene dynamics (SU-4 to SU-7)

The fluvial and marine fill of the incised estuary started some time before 10.7 cal. ka BP (Dabrio et al. 2000) when the sea level raised to 30 m below MSL (Lario et al. 2002). During the postglacial transgression, sea level raised rapidly until 7500-6500 cal. a BP in the Gulf of Cádiz. This was followed by a Holocene high stand phase (Goy et al. 1996; Boski et al. 2002; Lario et al. 2002; Fletcher et al. 2007) that lasts until today. Field observations show that the easternmost point reached by the sea during the transgression seems to be still downstream from the study area, as no marine sediments were found inside the examined profile sections.

At the beginning of the Holocene, extensive sedimentation was detected in the Guadalete River valley, with the deposition of up to 5-6 m of sands (SU-5a, SU-5b) at the base in the La Ina section (Figures 3.10B, 3.14). On the basis of radiocarbon dating of soil layers at the top of these sediments (see below), the sedimentation age of SU-5a and SU-5b is estimated at about 10 cal. ka BP, i.e. during an arid period (Pons & Reille 1988; Cacho et al. 2001; Fletcher et al. 2007; Figure 3.14). Pedogenetic overprinting of SU-5b with associated soil features (high clay contents, red-brown color and numerous large-sized calcareous concretions) found in several places (e.g. La Medina) indicate that this aggradation period was followed by a long period of pedogenesis, dated between about 9 and 8 cal. ka BP (Figure 3.11B, 3.12B). These observations are well in accordance with the findings of Fletcher et al. (2007), who described the onset of a warm, moist and oceanic Mid-Holocene Optimum with increased precipitation at 9.1 cal. ka BP along the northern Gulf of Cádiz (Figure 3.14) (see also Zazo et al. 2008). Likewise, Pons & Reille (1988) stated a thermal humid optimum starting at 9.2 cal. ka BP that last until sometime before 7.2 cal. ka BP in Padul in Southern Spain, although the studied record is situated about 300 km away at the much higher foot slopes of the Sierra Nevada. The onset of formation of the Laguna de Medina lake record around 9 cal. ka BP could also provide evidence for a more humid period, although Reed et al. (2001) found more or less unstable water levels until 8 cal. ka BP (Figure 3.14).
Figure 3.14. Compilation of Late Pleistocene and Holocene periods of sedimentation, incision and floodplain stability distinguished in the floodplain of the lower and upper downstream sections of the Guadalete River. Results are plotted against other palaeoenvironmental information from local or regional contexts to indicate climate forcing that controls fluvial sedimentation dynamics in the Guadalete River catchment.
Floodplain sediments of the Guadalete River indicate the end of soil formation at 8046±108 cal. a BP. At that time, a major erosive period affected the whole floodplain (Figure 3.10B), before the onset of a sedimentation period at around 7851±93 cal. a BP (SU-6). Responsible for these dynamics was a frequent flooding of the floodplain changing from an initially erosive towards more accumulative character. This evolution may be allocated to a regional major climate and environmental change at 8 cal. ka BP (Mayewski et al. 2004), documented in many proxy records. A cooling event in the Gulf of Cádiz (Cacho et al. 2001) coincides with desiccation phases reported by Reed et al. (2001) (Figure 3.14) and Pons & Reille (1988). Fletcher et al. (2007) similarly document a forest decline related to an arid interval between 7.85 and 7.39 cal. ka BP (Figure 3.14). Particularly impressive is the complete absence of settlement traces between 8.5 and 7.4 cal. ka BP (Berger & Guilaine 2009; Cortés Sánchez et al. 2012) that falls together with a gap between the Mesolithic and the Neolithic era. Cortés Sánchez et al. (2012) explain this gap by an environmental crisis caused by lower Northern Hemisphere summer solar insolation, most probably under participation of the 8.2 ka-event (Bond et al. 1997; Berger & Guilaine 2009). Following from this, the deposition of unit SU-6 in the Guadalete floodplain is assigned to a period of system instability, which is manifested in weakening of vegetation, higher runoff, sediment mobilization and corresponding sedimentation in floodplains (Vandenberghhe 2003; Wolf et al. 2013).

Furthermore, the significance of fluvial sedimentation processes around 8 cal. ka BP even in the transitional area to the marine environment is expressed by high fluvial input of sandy material into the estuaries (Boski et al. 2002) and even into the continental shelf (Lobo et al. 2001). At the Guadalete estuary an up to 15 m deep tidal ravinement channel was refilled with fluvial sands between 8 and 6.9 cal. ka BP (Dabrio et al. 2000), which is well in accordance with sedimentation dynamics in the Guadalete downstream section.

3.5.1.3 Mid-Holocene dynamics (SU-8)

The beginning of mid-Holocene period in the Guadalete River is mainly characterized by pedogenesis, that took place prior to 6045±129 cal. a BP and after 5568±83 a / 5128±158 cal. a BP. In between, deposition of flood loams occurred (Figures 3.11A, B). This evolution is explained by a climate shift at about 7 ka towards higher humidity: More humid conditions between 7 and 6 ka were found by Yanes et al. (2011) in southern Spain and Taylor et al. (1998) in south-central Spain. Environmental evidences for this are also recorded in vegetation (Fletcher et al. 2007; Figure 3.14), and in lake level: at the Laguna de Medina, a maximal lake level was observed between 7 and 6.7 cal. ka BP (Reed et al. 2001; Figure 3.14) and coincides with the marine transgression maximum in the Gulf of Cádiz (Goy et al. 1996; Zazo et al. 1996, 2008). Pollen analyses suggest that these relatively humid conditions occurred until 4.9 cal. ka BP (Fletcher et al. 2007; Figure 3.14) and the lake-level record of Laguna de
Late Pleistocene and Holocene fluvial dynamics of the Guadalete River

Medina shows evidences for relatively high lake-levels between 6.7 and 5.5 cal. ka BP with temporal desiccation phases between 6.7 and 6.2 cal. ka BP and at 5.9 cal. ka BP (Reed et al. 2001; Figure 3.14).

The sedimentation period between about 6 and 5.5 ka is consistent with evidences for increasing fluvial influence reported by Schneider et al. (2010) for estuaries in the Algarve region between 6.7 and 5.5 cal. ka BP. A remaining issue concerns the respective role of climate and anthropogenic influences. Due to increased pressure of exploitation, the consolidation of late Neolithic tribal communities in the wider area of Cádiz at around 6 to 5.7 cal. ka BP was actually shown to lead to an increase of slope erosion in the surroundings of settlement areas (Ruiz Gil & López Amador 2003; Ramos Múñoz & Pérez Rodríguez 2008). The impact of human societies at a catchment scale remains, however, contentious.

3.5.1.4 Mid-Holocene aridity collapse (SU-9a to SU-9c)

The lack of older sediments in the upper downstream section indicates that a significant erosion of floodplain sediments occurred prior to 4.6 cal. ka BP (Figures 3.4, 3.10A). It is unlikely that high-magnitude extreme flood events have been involved in these erosion processes as the lower downstream section seems relatively unaffected. Taking account for the mean width of the Holocene floodplain (about 700 m), it is more likely that intense meandering of the river course caused strong reworking of floodplain sediments due to meander shifting and undercutting of river banks. A pronounced system turnaround is indicated by a large quantity of trunks and botanical macrofossils (Figure 3.5) that were found within a thin gravel layer covering the erosion surface of the underlying marls. This “palaeo-forest” is covered by at least 3 m of coarse gravels (SU-9a). Species composition of samples B4 and B5 indicate the presence of riparian forest with a significant proportion of oak, especially cork oak (Quercus suber L.).

The radiocarbon age of 4609±188 cal. a BP obtained on a trunk of ash-tree (Fraxinus sp.), is consistent with a higher dryness (López Sáez et al. 2002) that allowed the destabilization of the environment and the burying of trees by gravel deposition. Extensive gravel deposition actually points to higher discharges probably caused by higher-magnitude events or/and by higher surface runoff due to diminishing of vegetation. The sedimentation of fine material (SU-9b) stopped abruptly sometime after 4.3 cal. ka BP (Figures 3.8A, B) in the upper downstream section and after 3788±87 cal. a BP (Figure 3.11A) in the lower downstream section, before floodplain stability led to soil formation in SU-9b and SU-9c. It is questionable whether there is an equivalent to unit SU-9c in the upper downstream section. However, the complexity of fluvial dynamics with out-of-phase sedimentation along a given river valley (see Figure 3.14), is established (Schumm 1973).

Similar periods of fluvial activity were found by Faust et al. (2000), Benito et al. (2008), Uribeiarrea & Benito (2008) and Wolf et al. (2013) in Spain. Moreover, for Tunisian river catchments an onset of significant floodplain sedimentation at 4.7 cal. ka BP was observed by Zielhofer et al. (2004, 2008) and
attributed to higher aridity. Around 5 cal. ka BP a global climate change (Steig 1999) introduced substantial changes in various ecosystems. In the western Mediterranean, it may have been associated with an increased aridity. Even though the onset of sedimentation in the Guadalete floodplain apparently coincides with the onset of a mid-Holocene cooling phase in the North Atlantic (Bond et al. 2001), it is possible that terrestrial ecosystems in the Mediterranean were already affected by higher aridity since 5 cal. ka BP (Zazo et al. 2005; Fletcher et al. 2007; Figure 3.14) or even earlier (Borja et al. 1999; Jalut et al. 2000; Reed et al. 2001; Carrión 2002). In that case, the delay in the response of geomorphic systems could be explained by different response times to climatic fluctuations, vegetation systems and geomorphic systems, or a buffer capacity of the environment towards external and internal pressures that has been exceeded by increasing aridity. However, in this context it should also be noted that between 5 and 4 cal. ka BP the Chalcolithic culture was highly developed and widespread in southwestern Spain (López Sáez et al. 2002). The Chalcolithic was characterized by an increase of deforestation and agricultural land-use (Cruz-Auñón Briones et al. 1992; Gavilán Ceballos 1997; Willms 1997; Fletcher et al. 2007; Ramos Múñoz & Pérez Rodríguez 2008; Schneider et al. 2010) and even mining activities are documented for the middle and upper catchment of the Guadalete River, primarily with the intention to produce silex (Cruz-Auñón Briones et al. 1992; Ramos Múñoz 1998). Although serious anthropogenic influences on the landscape before 2 cal. ka BP are often negated (e.g. Yll et al. 2003), agriculture or other forms of land use had the potential to amplify soil erosion processes, particularly if the landscape was already affected by climate change. However, beside the fact that the sediments of SU-9b (Figure 3.8B) are partly comprised of eroded soil horizons, no evidences for anthropogenic influences could be found in the study area.

3.5.1.5 Late Holocene dynamics (SU-10 to SU-12)

No significant sedimentation was found until the Roman period. Lateral erosion, initiated by river meandering, allowed mid-Holocene successions to be merely distributed in distal positions of the upper downstream section. During this time, increasing aridity (López Sáez et al. 2002; Martín-Puertas et al. 2010) with numerous desiccation events (Reed et al. 2001; Fletcher et al. 2007; Figure 3.14) and intensification of forest clearance, cereal cropping and livestock production (Faust & Diaz del Olmo 1997; Gómez Ponce et al. 1997; Willms 1997; Fletcher et al. 2007; Ramos Múñoz & Pérez Rodríguez 2008) are documented for southwestern Spain. Reed et al. (2001) reported an accelerated infilling of the Laguna de Medina since 3.4 cal. ka BP, allocated to anthropogenic impact (Figure 3.14). Borja et al. (1999) described strong aeolian activity around Cádiz starting at about 3 cal. ka BP, and Ramos Múñoz & Pérez Rodríguez (2008) observed large environmental transformations caused by new political structures and social developments initiating colluviation and alluviation processes, especially in large river systems. In the Guadalete River,
sedimentation seems to have started later: Alluviation and colluviation processes on the Late Pleistocene terrace level started at around 2245±93 cal. a BP, when a presumably Phoenician settlement has been abandoned and buried by blackish sediments containing a plenty of brick and pottery fragments (Figure 3.3). In the active floodplain, the study of the Spinola profile indicates an onset of sedimentation sometime before 1969±72 cal. a BP, with more than 1 m of loamy, organic rich material being deposited (Figure 3.6B), documenting the admixture of eroded topsoil material. The SU-10 unit at the profile Rancho Romero (Figure 3.8B) might have also been deposited at the same period. We assume that sediment mobilization and shifting continued during the Roman occupation period that induced growing pressure of exploitation and land use within the Guadalete catchment (Willms 1997). This sedimentation during the Roman time is not an isolated observation: in neighboring areas, Faust et al. (2000) and Schneider et al. (2010) found increased fluvial sedimentation dynamics in a period starting at about 2.3 cal. ka BP. However, decisive driving forces cannot be clearly separated. On the one hand, clear indications of Phoenician and Roman mining and smelting were observed, e.g. in sediments of the Zoñar lake (Martín-Puertas et al. 2010; see also Yll et al. 2003) as well as numerous evidences for deforestation and intensified agriculture. On the other hand, a dry climatic interval occurred between 2.1 and 1.8 cal. ka BP in the same area (Martín-Puertas et al. 2009; Figure 3.14). Even if desiccation events in the surrounding area are reported only later, around 1.8 to 1.7 cal. ka BP (Reed et al. 2001; Fletcher et al. 2007; Figure 3.14), it must be assumed that the observed evolution was the result of a combination between human influence and climate.

An increased progradation of the Valdelagrana spit bar system at the Guadalete estuary since 2.4 cal. ka BP (Zazo et al. 1996) points to higher fluvial sediment input that fits well the sedimentation dynamics found in the upper downstream section. The existence of a Roman bridge between 1.9 and 1.8 cal. ka BP that crossed different spit units in the Guadalete estuary (Gómez Ponce et al. 1997) could count for a temporary completion of spit growing, and thus decreased fluvial sediment delivery. Evidences from the study area actually show that the Guadalete floodplain remained stable until 1.1 cal. ka BP, apart from ongoing gravel deposition within the channel belt (Figures 3.6D, 3.14). At about 1.1 cal. ka BP incision took place in several channels of the Guadalete River. At the same time, Dias et al. (2000) found increasing supply of terrigenous material to the Gulf of Cádiz shelf. This incision might relate to a slight fall of sea-level recorded in the area until 1 cal. ka BP (Hernández-Molina et al. 1994). After a period of stability indicated by clay accumulation and plant growth (Palmaceae) even in proximal or channel positions (Figure 3.9C, profile José Antonio), a new period of loamy sedimentation took place. This was dated at 993±61 cal. a BP at the meander of El Torno (Figure 3.6D) and 848±81 cal. a BP at the floodplain channels nearby profile Rancho Romero (Figure 3.8A). Especially in the latter, the sediments are very different compared to those previously deposited: they are dark and humic, and probably originate from topsoil erosion of the surrounding Campiña marl landscape. As the Tertiary and Triassic marls were shown to be sensitive to soil erosion processes (Faust 1995; Faust & Schmidt 2009), this change may relate to land use changes in the
catchment. In addition to human influence, this enhanced soil erosion may have been intensified by the drier conditions and increased rainfall variability. These conditions are typical for the Medieval Climate Anomaly (Borja et al. 1999; Reed et al. 2001, Figure 3.14; Martín-Puertas et al. 2010; Moreno et al. 2012b) that relate to a continuous positive mode of the North Atlantic Oscillation as stated by Trouet et al. (2009) or Moreno et al. (2012b). Thus, once more we interpret a mixture between human and climate forcing affecting the landscape during the Medieval times.

3.5.1.6 Increased dynamics during the Little Ice Age (LIA) (SU-13a to SU-14)

Between the mid-Holocene arid period and the end of the Medieval Climate Anomaly, intense river meandering and lateral erosion occurred in the Guadalete floodplain. Thus, accommodation space for new sediments was large at the beginning of the LIA. At 400 cal. a BP a very short (a few years/decades) but significant sedimentation took place (Figure 3.14). The whole proximal area of the river valley was filled up with laminated pale and humic material (SU-13b) originating from the Campiña marl landscape (Figures 3.6E, 3.8A). Channels in the La Ina section are also likely to have been refilled during that time (Figure 11C, coring LA INA-5). Intensification of fluvial dynamics is actually widely reported for the LIA in Iberia (Faust et al. 2000; Benito et al. 2003; Uribelarrea et al. 2003; Benito et al. 2008; Ortega & Garzón 2009; Bullón 2011; Fletcher & Zielhofer 2013; Wolf et al. 2013). Numerous studies around the Gulf of Cádiz provided evidences for a drastic increase of sediment input into the shelf and rapid infilling of estuaries since 500 cal. a BP (Lario et al. 1995; Dabrio et al. 2000; Dias et al. 2000). Additionally to strong human impact (e.g. deforestation and agriculture), increased aridity is reported during that time (Dabrio et al. 2000; Rodrigo et al. 2000), which is confirmed by a desiccation event around 400 cal. a BP at the Laguna de Medina (Reed et al. 2001; Figure 3.14). Martín-Puertas et al. (2010) refers to generally wetter conditions after 500 cal. a BP leading to higher sediment input into different sediment traps in southern Spain, while controversiably Bullón (2011) points out that fluvial dynamics were characterized by large floods with long lasting droughts in between. Similarly, arid conditions are documented for Southwestern Spain as well. Thus, we suggest higher precipitation variability causing heavy run-off and increased soil erosion as well as floodplain sedimentation around 400 cal. a BP. These dynamics may either be linked to a positive NAO index between 470 and 390 cal. a BP or to the transition period from a positive towards a short phase negative NAO index at about 400 to 390 cal. a BP (Trouet et al. 2009). At about 120 cal. a BP, a moderate erosive phase occurred prior to contemporaneous sedimentation (Figure 3.6E) that coincides with increased human impact since this time (Dabrio et al. 2000) as well as another shift of the NAO index from positive to negative mode (Trouet et al. 2009).
3.6 Conclusion

Studies of the stratigraphic records of the lower Guadalete River indicate that Late Pleistocene and Holocene fluvial dynamics relate to various driving forces. Sea-level changes have been a determining factor, notably during the Late Pleistocene and until the early Holocene, when phases of sea-level fall involved the lowering of the base level, leading to strong river incision and intense clearing-out of floodplain sediments shortly before the Bolling and Allerød interstadials. However, temperature decrease and higher aridity also played a decisive role concerning diminished vegetation cover and increased runoff variability that are fundamental requirements for enhanced dynamics in glacial times. Despite the chronological framework remains questionable for the Late Pleistocene sediments, a very unstable environment must have prevailed leading to high runoff peaks and sediment supply into the floodplain under most likely arid conditions. While the subsequent Bolling and Allerød interstadials are characterized by increased humidity and soil formation, we suggest continued river incision for the Younger Dryas. In the course of a rapid sea-level rise until the early to mid-Holocene, fluvial evolution should be increasingly related to environmental conditions resulting in landscape stability or instability. Hence, the climate forcing was obvious during humid periods (e.g. until 8.0 and until 6.2 cal. ka BP), with the development of soils that remain preserved by vegetation cover. Pedogenesis also took place during more arid periods (e.g. between 4.3 and about 2.4 cal. ka BP), as landscape stability allowed the sediment supply to be negligible. In contrast, periods of floodplain sedimentation are reflective of landscape instability that often corresponds to arid climate. The early Holocene was also characterized by accumulation of sandy material within the floodplain that possibly correlates with higher aridity prior to 9.2 cal. ka BP (Reed et al. 2001; Fletcher et al. 2007; Figure 3.14) with associated delay of vegetation development as well as corresponding runoff patterns. All subsequent sedimentation phases, in particular after 7.9, after 6.1, between 4.6 and 4.3, around 2.0, between 1.1 and 0.8 and since 0.5 cal. ka BP took place during periods of increased aridity (Figure 3.14). Since increasing aridification results in both vegetation decrease and increased hydrological events, the increase of runoff leads to slope erosion and floodplain sedimentation (Vandenberghe 1995; Gómez-Paccard et al. 2013; Wolf et al. 2013). A modification of this general scheme was found around 400 cal. a BP, when a very short but heavy sedimentation led to the complete fill-up of the meander belt. A switch of the NAO index mode towards negative values detected by Trouet et al. (2009) at 390 cal. a BP could have been associated with heavy rainfall, affecting the previous arid and highly sensitive landscape of western Andalucía.

Despite the Guadalete River fluvial response was largely driven by climate, human forcing should also be taken into account. Our investigations could not isolate the respective influence of human vs. climate change. However, it is likely that deforestation and cultivation activities raised the environmental pressure imposed by increased aridity. In contrast, since human practices well adapted to the environment
might have protective effects on the earth surface (Faust 1993), erosion may mainly occur during “wasteland periods” or cultural declines.

Concerning coastal sedimentation, at 4.4 - 2.7 cal. ka BP, 2.4 - 0.8 cal. ka BP and during the last 500 years, increased accumulation of spit barriers were documented in the Guadalete estuary (e.g. Zazo et al. 1996; Dabrio et al. 2000) that correlate with increased sedimentation dynamics along the lower Guadalete River. Thus, fluvial sediment input to the coastal area seems crucial for spit bar formation that in turn may be reflective for dynamics within the river catchment.

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References


3 Late Pleistocene and Holocene fluvial dynamics of the Guadalete River


Carrión, J. S. 2002: Patterns and processes of Late Quaternary environmental change in a montane region of southwestern Europe. Quaternary Science Reviews 21, 2047–2066.


Finlayson, C. 2008: On the importance of coastal areas in the survival of Neanderthal populations during the Late Pleistocene. Quaternary Science Reviews 27, 2246-2252.

Fletcher, W. J., Boski, T. & Moura, D. 2007: Palynological evidence for environmental and climatic change in the lower Guadiana valley, Portugal, during the last 13 000 years. The Holocene 17, 481–494.


3 Late Pleistocene and Holocene fluvial dynamics of the Guadalete River


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Schneider, H., Höfer, D., Trog, C., Busch, S., Schneider, M., Baade, J., Daut, G. & Mäusbacher, R. 2010: Holocene estuary development in the Algarve Region (Southern Portugal) – A reconstruction of sedimentological and ecological evolution. Quaternary International 221, 141–158.


Late Pleistocene and Holocene fluvial dynamics of the Guadalete River


4 Western Mediterranean environmental changes

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Western Mediterranean environmental changes: Evidences from fluvial archives

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Abstract: When dealing with current and past landscape evolution, a key issue addresses responses of geomorphic systems to the large number of influencing variables. Identifying morphodynamic phases and revealing interrelations with specific driving forces are demanding tasks for Quaternary research. In this paper, we present late Pleistocene and Holocene fluvial sedimentation patterns of three Western Mediterranean river catchments, namely Jarama River, Guadalete River and Guadalquivir River that extent along a climatic transect from semi-humid SW-Spain to semi-arid central Spain. These studies are based on extensive field work conducted on 36 exposures and 13 drillings in floodplain positions. Field data is supported bygeochemical analyses, while the chronological framework was obtained from the analyses of 70 radiocarbon samples. Results show distinct patterns of fluvial sedimentation as well as soil formation linked to floodplain stability for each river catchment. On regional or catchment scale, pollen stratigraphical correlation and comparison with lacustrine records show that fluvial dynamics have a strong reaction to climatic shifts, with phases of high fragility characterized by catchment erosion and floodplain sedimentation in response to climatic aridification events and phases of climate change in general. The comparison of the examined river systems reveals that periods of supra-regional floodplain sedimentation in several catchments occurred from 8.0 to 7.0, 5.0 to 3.8, 2.2 to 1.5, and around 1.0 as well as 0.4 ka cal. BP, while we found periods of supra-regional soil formation from 13.3 to 12.7, 7.0 to 5.1 (with a short interruption around 6.0 to 5.5 ka), 2.8 to 2.3 ka, 1.4 to 1.2 ka, and 0.8 to 0.5 ka cal. BP. Beside these consistencies we found deviating dynamic patterns that are apparently expressed in terms of differing onset and offset, differing durations, or even the lack of fluvial system response. The main reasons for this can be seen in different regional climate condition and impacts of further influencing factors, or in different levels of sensitivity of the river catchments that may be controlled by initial hydrological conditions, catchment size, or the degree of anthropogenic influence. A larger scale assessment shows that fluvial dynamic patterns are hardly comparable across entire Spain due to strong spatial heterogeneity of physiographic and climatic conditions on the Iberian
4 Western Mediterranean environmental changes

Peninsula, in particular when areas are influenced by different circulation systems (e.g. regions influenced by the Atlantic Ocean vs. regions influenced by the Mediterranean Sea). However, the consideration of North Atlantic marine records reveals a certain coupling between North Atlantic coolings, atmospheric processes leading to arid climate over large parts of Spain, as well as increased landscape instability including strong fluvial sedimentation activity. Attendant atmospheric conditions are discussed.

Keywords: Spain, Western Mediterranean, Fluvial dynamics, Fluvial archives, Climate change, Landscape evolution
4.1 Introduction

Archive investigation for the purpose of environmental and climate change is a highly acclaimed research field in the geosciences for several decades now. Given the variety of terrestrial records (see e.g. Magny 2004, Mayewski et al. 2004, Wanner et al. 2008, Fletcher and Zielhofer 2013, Moreno et al. 2014) that are used to investigate climatic shifts and their impact on the environment in the past, fluvial archives may play a specific role, since river systems respond to a multitude of environmental influences. Among the various kinds of fluvial archives, especially floodplain records that mainly consist of overbank fines are assumed to be sensitive towards catchment behavior (e.g. Lane and Richards 1997, Blum and Törnqvist 2000, Vandenberghe et al. 2010) as they inhere a wide range of fluvial processes that take place in a river catchment. For the buildup of cohesive floodplain records generally two things are needed: (1) sediment delivery from the catchment that requires superficial soil erosion, and (2) a certain degree of transport capacity for shifting eroded material to floodplain positions. This concept is complicated by a series of non-linear dependencies (see e.g. Walling 1983, de Vente et al. 2007) but describes the fundamental significance of floodplain records. A basic question is to what degree and in which manner fluvial dynamics are driven or at least influenced by climatic factors. Aggravatingly, potential effects of climate are overprinted by tectonics, base-level changes, anthropogenic impact or intrinsic forcing (Schumm 1973, Pope and van Andel 1984, Blum and Törnqvist 2000, Vandenberghe and Maddy 2001, Hoffmann et al. 2009, Vandenberghe et al. 2010, Cordier et al. 2014), preventing to deduce direct relationships between climate and fluvial dynamics. Considering the variety of parameters, the interpretation of fluvial archives is a difficult matter, particularly in view of problems like equifinality, divergence or multiplicity as already Schumm (1991) pointed out. However, the feasibility of climatic interpretation of fluvial records could be convincingly demonstrated (Törnqvist 2007, Fletcher and Zielhofer 2013, Wolf et al. 2013, von Suchodoletz et al. 2015), although a careful handling of non-climatic parameters is obviously needed. Apart from assessing the specific reaction of fluvial systems and landscapes on climate influences (e.g. dynamic patterns in relation to the gradient of climate change), outstanding issues relate to system connectivity and system response times, not only in a spatial context but likewise concerning interdependencies of climate, vegetation, soil and geomorphological systems. Another pending question belongs to the spatial variability of landscape dynamics, or more precisely, how reliable are local or regional findings when they are placed in a supra-regional context? The spectrum ranges from regionally specific dynamics proceeding on rather small spatial scales, to supra-regional dynamics that take place across long distances. In view of the regional heterogeneity of physiographic configurations on the Iberian Peninsula it is conceivable that even large-scale climatic impulses induce divergent system responses in different environmental conditions, which, for example, should appear in form of diverging fluvial dynamics in various river catchments.
In order to examine floodplain records for the purpose of reconstructing palaeoenvironments and stages of landscape evolution, floodplain sediments of selected river catchments in Spain have been investigated (see also Wolf et al. 2013 and 2014). Due to its fragility concerning climate changes and related earth shaping processes, the Western Mediterranean realm is particularly well suited for such research. The main objective was to obtain a solid fluvial stratigraphy for each river catchment based on a sufficiently large number of studied profile sections to minimize elements of randomness and singularity. Based on this, fluvial sedimentation histories supported by reliable chronological resolution should enable a direct comparison with other archives of environmental relevance in a regional context. In this way, it should be possible to assess the fluvial response on changes of external parameters, respectively to identify driving forces behind fluvial dynamics. Particularly challenging in this context is to shed some light on the constantly recurring question, whether flooding and floodplain aggradations take place in times of arid or rather in times of humid climate conditions (see review in Fletcher and Zielhofer 2013). The examined river systems are recently situated in areas of different annual values of precipitation. A comparison of the different fluvial dynamic patterns should on the one hand allow considering the geographic scope of fluvial dynamics and determining factors and, on the other hand, permit to assess the importance of initial precipitation regimes for kind and character of fluvial responses including response time and duration.

In this study, new results are presented that, together with findings already shown in Wolf et al. (2013) and Wolf et al. (2014), will be intensively discussed to address above-mentioned issues.

4.2 Study area

The studied catchments of the rivers Guadalete, Guadalquivir and Jarama are distributed along a transect reaching from the semi-humid southwestern part of Andalucía (SW-Spain) to the semi-arid area of the eastern Tajo Basin (Central Spain) (Lautensach 1964) (Fig. 4.1A). All catchments are connected to Atlantic river basins and are therefore hydro-climatically influenced by Atlantic air masses that may provide intense rainfall during winter season, especially in case of negative North Atlantic Oscillation (NAO) modes (Trigo et al. 2004). The climate shows a significant gradient and becomes gradually more continental with annual temperature amplitudes of 13 to 16°C in the Guadalete catchment and 19 to 21°C in the Jarama catchment (Lautensach 1964). Mean annual precipitation is very inhomogeneous on catchment-scale due to strong altitudinal contrasts but generally decreases further inland. In the Guadalete catchment close to the Atlantic Ocean, precipitation varies from 646 mm/a in Jerez de la Frontera (36°45´N/06°04´W) (Sträßer 1998) nearby the coastline to more than 2000 mm/a in the Sierra de Grazalema (Hidalgo-Muñoz et al. 2011). In the Jarama catchment large parts of the Madrid Basin point to annual precipitation of 400 to
Figure 4.1: A. Location of the three studied river catchments in Spain. B. Section of the middle Guadalquivir River reach around Córdoba with location of studied profile sections. C. Detailed map of the lower Jarama River with studied profile sections. D. Detailed map of the lower Guadalete River with indication of studied profile sections and coring positions.
Western Mediterranean environmental changes

500 mm, with 456 mm in Madrid (40°25′N/03°41′W) (Sträßer, 1998) but in the upper part of the Sierra de Guadarrama precipitation rises to 1400 mm/a (Palacios et al. 2012). The Guadalquivir Basin with an area of about ~57,000 km² offers a wide range of climatic conditions and precipitation varies from 400 to 500 mm/a e.g. in the basins of Loja and Baza to more than 1400 mm/a in the Betic Range (Anderson et al. 2011).

4.2.1 Jarama River

The Jarama River drains a catchment area of ~11,500 km² that is located in central Spain (Fig. 4.1A). It originates in the Sierra de Guadarrama at 2120 m above mean sea level (MSL) and after a total flow length of some 180 km it converges with the Tajo River at 485 m MSL. The greater part of the catchment is taken up by the Madrid Basin, a tertiary depression between altitudes of 500 to 800 m (MSL) that was filled up with several hundred meters of Miocene sediments. With a concentrical arrangement these sediments consist of arkosic alluvial fan material in the outer parts, followed by calcareous marls, and finally evaporitic gypsum marls in the center (Calvo et al. 1996). Towards the northwest, the basin is bordering the Spanish Central System, where igneous and metamorphic rocks reach elevations up to ~2400 m MSL. Towards the northeast the catchment is framed by Mesozoic rocks of the Iberian Range. Since the middle Miocene the Madrid Basin is subject to severe tectonic activity linked to large-scale Betic compressions (Andeweg et al. 1999). Corresponding fault lines and flexures are generally orientated NE-SW and determine the pathways of the fluvial drainage network (e.g. Fig. 4.1C). Moreover, mapped fault lines across the river valley with associated knick-points of the valley floor (Silva et al. 1988) give evidence for seismic activity during the Pleistocene (De Vicente et al. 2007) and on a moderate level until today (Tejero et al. 2006). Since the lower catchment is dominated by gypsum marls strongly vulnerable to bulging and solution processes, widespread indication of halokinetic deformation occur along the river valleys. Along its lower reach, the Jarama River actually incised up to a depth of 60 to 80 m into gypsum marls, leading to steep escarpments. Here, the floodplain reaches a width of 2 to 3 km. The middle course of the Jarama is characterized by a very narrow Holocene floodplain incised in Pleistocene terraces, whereas the lower course shows a wide Holocene floodplain. Here, Holocene sediments spread to a considerable thickness of up to 7 m. Thus, the majority of the studied profiles is situated in the lowermost river section (Fig. 4.1C) that shows a mean floodplain slope of 1.7 ‰ and a meandering river pattern with medium sinuosity of 1.2 (Uribellarea et al. 2003), bearing in mind recent discharge regulation and gravel mining.

In the Madrid Basin dominant land use units are shrublands, pastures and farmland. Mountain areas are characterized by woodland that is transformed into shrub formations in case of degradation.
4.2.2 Guadalete River

The catchment of the Guadalete River encloses an area of 3,400 km² and is situated in SW-Spain, on the border between Lower and Upper Andalucía (Fig. 4.1A). The Guadalete River originates at an altitude of 1100 m MSL. After a stream distance of 170 km it enters the Gulf of Cádiz. The upper catchment covers Jurassic to Tertiary limestones and marls and early Miocene sandstones of the Betic Range (Moral-Cardona et al. 1996) with elevations between 300 and 1600 m MSL and a rough and steep relief. The middle and lower catchment covers the undulating landscape of the Campiña de Cadiz that is composed of Triassic marls and Miocene marls, limestones and calcarenites (Lautensach 1964). Close to the estuary that reaches a width of 8 km, the Guadalete River runs through the brackish environment of the Marismas, a mudflat area with an elevation of up to 3 m MSL. Along the river valley, a sequence of 5 Pleistocene terraces was found by Diaz del Olmo (1989) between 3 and 50 m above recent floodplain level that originate from mid- to late Pleistocene times (Rodriguez Vidal et al. 1993). At a distance of about 25 km from the coastline, the youngest Pleistocene terrace descends below the Holocene floodplain level (terrace crossing point at the limit between lower and upper downstream section) (Fig. 4.1D).

Along the middle river course the Holocene floodplain is very narrow and widens up to 1.5 km along the lower course with a meandering river pattern and a sinuosity between 1.32 and 1.78. Besides the general tectonic uplift of the area (Zazo et al. 1999) and neotectonic activities that lead to tectonic lineation and earthquakes (Silva et al. 2005, Medialdea et al. 2009), Triassic and Tertiary marls of the lower catchment are highly vulnerable to halokinetic deformation like bulging and diapirism. Large parts of the catchment are used for intense agriculture and pasture while Mediterranean maquis and shrubs as well as fragmented oak forests are restricted to the mountain area of the upper catchment.

4.2.3 Guadalquivir River

The Guadalquivir River drains a catchment area of ~57,000 km² and covers the larger part of Andalucia (Fig. 4.1A). It originates in the Sierra de Cazorla at an altitude of 1400 m MSL and enters the Gulf of Cádiz after a stream distance of 657 km. Only two profile section were studied nearby Córdoba, along the lower middle course of the river (Fig. 4.1B), in order to supplement with our detailed studies from the Jarama in the north and the Guadalete in the south. In the middle and lower reach the Guadalquivir River runs through a permanently lowering foreland basin between the Betic Cordillera in the south and the Paleozoic rocks of the Sierra Morena in the north. The beginning of the sedimentary infill dates back to the middle Miocene (for further information see Salvany et al. 2011). Bordering areas to the south of the recent river valley are predominantly comprised of Miocene marls belonging to the Campiña de Córdoba, currently an intense cultivated area. Baena Escudero and Diaz del Olmo (1994)
described up to 14 different terrace levels along the river valley. In the Córdoba area, the recent river shows a meandering pattern and a medium sinuosity of 1.31 with a floodplain width ranging between 0.25 and 2 km (Uribelarrea and Benito 2008).

4.3 Methods

Fieldwork was carried out between 2009 and 2012. About 36 exposures, mostly in gravel pits, were studied in the field together with 7 percussion drillings and 6 hand augerings. Sedimentological and pedogenetic findings were used to identify and differentiate sediment units. In this context, particular attention was given to the identification of erosion unconformities, soil formations and relocated soil sediment as well as cultural remains that permit a temporal placement or at least document certain human influence. In summary, 528 soil and sediment samples were taken from representative key profiles in order to confirm field observations and to distinguish between soils and soil sediments in ambiguous cases.

Standard analyses were implemented in the laboratory of the Department of Physical Geography at the Technische Universität Dresden, Germany. Grain-size analyses were conducted in form of pipette analyses and wet sieve techniques (Schlichting et al., 1995) after dispersing with sodium pyrophosphate and initial elimination of gypsum by dilution and centrifugation of respective samples (Frenkel et al., 1986; FAO, 1990). The amount of gypsum and dissolved salts has been determined by mass loss during grain-size analyses. Soil organic matter was measured via suspension and catalytic oxidation (TOC-VCPN / DIN ISO 16904). Carbonate content was determined by measuring the carbon dioxide gas volume after adding hydrochloric acid in a Scheibler apparatus (Schlichting et al., 1995). Total iron content was determined after pressure digestion with concentrated nitric and hydrofluoric acid using atomic adsorption spectrometry. Pedogenic iron content was measured after dithionite extraction using atomic adsorption spectrometry as well (Schlichting et al., 1995). The mathematical relationship between pedogenic iron and total iron is used as an indicator for weathering intensity (Zielhofer et al. 2009). For more detailed information see Wolf et al. (2014).

Radiocarbon dating was carried out on 70 samples of in situ and ex situ charcoals, wood, organic sediments, bones and mollusk shell fragments (see Tab. 4.1) in order to assess a temporal resolution of sedimentation and soil-formation periods. The measurements were performed by the AMS $^{14}$C laboratories in Kiel (KIA) and Erlangen (Erl), Germany, and Miami (Beta, United States), and all $^{14}$C ages were calibrated using CALIB 6.0 (Stuiver and Reimer, 1993) with the IntCaL09.14c calibration curve (Reimer et al., 2009) that has been extended to 50 ka cal. BP. The mean of the 2σ probability interval is usually used in the text and denoted in Table 4.1. All radiocarbon dating derived from existing studies were likewise calibrated in the above mentioned manner to ensure comparability. With regard to the discussion (section 4.5) it must be pointed out that we are convinced that radiocarbon dating method applied on fluvial
records provides quite reliable data, but the very uncertainties related to standard deviation and confidence interval are still restrictions with respect to response times and durations of processes.

Table 4.1 Radiocarbon dates obtained from Jarama, Guadalete and Guadalquivir River systems.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Lab no.</th>
<th>Material</th>
<th>Cal. age yrs BP</th>
<th>Significance</th>
<th>Sed. unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarama River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-293515</td>
<td>Organic sediment</td>
<td>26,150 ± 120</td>
<td>30,852 ± 279</td>
<td>Soil formation</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-293516</td>
<td>Branch</td>
<td>16,140 ± 70</td>
<td>19,193 ± 254</td>
<td>Filling of sinkhole</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>KIA 39205</td>
<td>Trunk (Populus sp.)</td>
<td>4475 ± 30</td>
<td>5132 ± 155</td>
<td>Start sedimentation</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-313498</td>
<td>Wood</td>
<td>3860 ± 30</td>
<td>4284 ± 126</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-204964</td>
<td>Branch</td>
<td>3750 ± 40</td>
<td>4109 ± 125</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>KIA 39206</td>
<td><em>ex situ</em> charcoal</td>
<td>3090 ± 30</td>
<td>3300 ± 78</td>
<td>Active sedimentation</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>KIA 39204</td>
<td>Charred plant material</td>
<td>2925 ± 25</td>
<td>3089 ± 114</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-204974</td>
<td>Branch</td>
<td>2870 ± 30</td>
<td>3007 ± 128</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>KIA 39210</td>
<td><em>in situ</em> fire plant</td>
<td>2870 ± 25</td>
<td>2982 ± 93</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>KIA 39209</td>
<td><em>ex situ</em> plant remains</td>
<td>2845 ± 25</td>
<td>2966 ± 95</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-301970</td>
<td><em>ex situ</em> charcoal</td>
<td>2730 ± 30</td>
<td>2838 ± 77</td>
<td>Active sedimentation</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Erl-15157</td>
<td><em>ex situ</em> charcoal</td>
<td>2094 ± 41</td>
<td>2120 ± 171</td>
<td>Active sedimentation</td>
</tr>
<tr>
<td>Aranjuez</td>
<td>Beta-301971</td>
<td><em>ex situ</em> charcoal</td>
<td>1610 ± 30</td>
<td>1484 ± 72</td>
<td>Active sedimentation</td>
</tr>
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<td>Aranjuez</td>
<td>KIA 39211</td>
<td><em>ex situ</em> charcoal</td>
<td>405 ± 25</td>
<td>423 ± 90</td>
<td>Active sedimentation</td>
</tr>
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<td>Cenex</td>
<td>Beta-300818</td>
<td>Organic sediment</td>
<td>33,290 ± 220</td>
<td>37,972 ± 768</td>
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<tr>
<td>Holcim</td>
<td>Erl-15163</td>
<td><em>ex situ</em> charcoal</td>
<td>&gt; 5,500</td>
<td>12,700 ± 143</td>
<td>Stagnant sed.</td>
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<td>Holcim</td>
<td>Erl-15164</td>
<td><em>ex situ</em> charcoal</td>
<td>39,762 ± 1053</td>
<td>43,789 ± 1502</td>
<td>Start soil formation</td>
</tr>
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<td>Holcim</td>
<td>Erl-15162</td>
<td><em>ex situ</em> charcoal</td>
<td>13,654 ± 236</td>
<td>16,493 ± 898</td>
<td>Active sedimentation</td>
</tr>
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<td>Holcim</td>
<td>Erl-15161</td>
<td><em>ex situ</em> charcoal</td>
<td>10,599 ± 45</td>
<td>12,537 ± 113</td>
<td>Stagnant sed.</td>
</tr>
<tr>
<td>Holcim</td>
<td>Beta-301972</td>
<td><em>ex situ</em> charcoal</td>
<td>4460 ± 40</td>
<td>5093 ± 200</td>
<td>Colluvial layer</td>
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<td>Peralta</td>
<td>Erl-15167</td>
<td><em>ex situ</em> charcoal</td>
<td>2044 ± 39</td>
<td>2009 ± 109</td>
<td>Active sedimentation</td>
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<td>Peralta</td>
<td>KIA 39218</td>
<td><em>ex situ</em> charcoal</td>
<td>2035 ± 30</td>
<td>2004 ± 104</td>
<td>Active sedimentation</td>
</tr>
<tr>
<td>Peralta</td>
<td>Erl-15166</td>
<td><em>ex situ</em> charcoal</td>
<td>1983 ± 39</td>
<td>1932 ± 104</td>
<td>Channel aggradation</td>
</tr>
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<td>Peralta</td>
<td>Beta-313499</td>
<td><em>ex situ</em> charcoal</td>
<td>1960 ± 30</td>
<td>1908 ± 79</td>
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</tr>
<tr>
<td>Peralta</td>
<td>Beta-300822</td>
<td>Bone collagen</td>
<td>1810 ± 30</td>
<td>1726 ± 97</td>
<td>Channel aggradation</td>
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<td>San Martin</td>
<td>Erl-15169</td>
<td><em>ex situ</em> charcoal</td>
<td>386 ± 37</td>
<td>413 ± 96</td>
<td>Active sedimentation</td>
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<td>San Martin</td>
<td>Erl-15168</td>
<td><em>ex situ</em> charcoal</td>
<td>307 ± 38</td>
<td>385 ± 89</td>
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<tr>
<td>Seseña</td>
<td>Erl-15159</td>
<td><em>ex situ</em> charcoal</td>
<td>6595 ± 38</td>
<td>7498 ± 67</td>
<td>End sedimentation</td>
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<td>Seseña</td>
<td>Erl-15160</td>
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<td>3103 ± 33</td>
<td>3317 ± 75</td>
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<td>Titulcia</td>
<td>Beta-300823</td>
<td><em>in situ</em> fire site</td>
<td>4490 ± 90</td>
<td>5152 ± 288</td>
<td>Soil formation</td>
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<td>Titulcia</td>
<td>Beta-300824</td>
<td><em>ex situ</em> charcoal</td>
<td>1690 ± 30</td>
<td>1612 ± 81</td>
<td>Cultural layer</td>
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Guadalete River

<table>
<thead>
<tr>
<th>Profile</th>
<th>Lab no.</th>
<th>Material</th>
<th>Cal. age yrs BP</th>
<th>Significance</th>
<th>Sed. unit</th>
</tr>
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<tbody>
<tr>
<td>Braza-II</td>
<td>Beta-293518</td>
<td>Trunk (<em>Fraxinus sp.</em>)</td>
<td>4050±40</td>
<td>4609±188</td>
<td>Start sedimentation</td>
</tr>
<tr>
<td>Braza-I</td>
<td>Erl-15179</td>
<td><em>in situ</em> macrofossil (<em>Urticaeae</em>)</td>
<td>3936±36</td>
<td>4381±133</td>
<td>Stability</td>
</tr>
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<td>Braza-III</td>
<td>KIA 39216</td>
<td><em>in situ</em> macrofossil (<em>Urticaeae</em>)</td>
<td>3940±50</td>
<td>4279±128</td>
<td>Stability</td>
</tr>
<tr>
<td>Braza-II</td>
<td>Beta-293517</td>
<td><em>in situ</em> macrofossil (<em>Urticaeae</em>)</td>
<td>320±40</td>
<td>391±89</td>
<td>Channel aggradation</td>
</tr>
<tr>
<td>Braza-I</td>
<td>Erl-15178</td>
<td><em>ex situ</em> charcoal</td>
<td>311±39</td>
<td>387±89</td>
<td>Active sedimentation</td>
</tr>
<tr>
<td>Braza-II</td>
<td>KIA 39215</td>
<td><em>ex situ</em> charcoal</td>
<td>170±25</td>
<td>143±143</td>
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</tr>
<tr>
<td>Braza-I</td>
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<tr>
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<td>KIA 39191</td>
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<td>1639±70</td>
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<td>MEDINA-3</td>
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<td>7190±40</td>
<td>8046±108</td>
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<td>INÁ-3</td>
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<td>Shell (mollusk)</td>
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<td>7851±93</td>
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<td>5128±158</td>
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<tr>
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<td>3788±87</td>
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</tr>
<tr>
<td>José Antonio</td>
<td>KIA 39207</td>
<td><em>in situ</em> macrofossil (<em>Urticaeae</em>)</td>
<td>911±28</td>
<td>830±86</td>
<td>Stability</td>
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<tr>
<td>José Antonio</td>
<td>Erl-15176</td>
<td><em>ex situ</em> charcoal</td>
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<td>576±66</td>
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<tr>
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<td>402±90</td>
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<td>La Barca</td>
<td>Erl-15156</td>
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<td>343±37</td>
<td>398±89</td>
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<tr>
<td>La Barca</td>
<td>Erl-15158</td>
<td><em>ex situ</em> charcoal</td>
<td>342±32</td>
<td>396±86</td>
<td>Active sedimentation</td>
</tr>
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<td><em>ex situ</em> charcoal</td>
<td>11,869±178</td>
<td>13,718±385</td>
<td>Active channel filling</td>
</tr>
<tr>
<td>Pozo Romano</td>
<td>Erl-15181</td>
<td><em>in situ</em> fire ground</td>
<td>2234±55</td>
<td>2245±93</td>
<td>Start colluviation</td>
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</table>
4 Western Mediterranean environmental changes

Table 4.1 continued.

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<th>Material</th>
<th>$^{14}C$ age yrs BP</th>
<th>Cal. age BP (2σ)</th>
<th>Significance</th>
<th>Sed. unit</th>
</tr>
</thead>
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<tr>
<td>Pozo Romano</td>
<td>Beta-294966</td>
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<td>GE-1</td>
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<tr>
<td>Rancho Romero</td>
<td>KIA 39213</td>
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<td>5436±41</td>
<td>6216±90</td>
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<td>GE-9c</td>
</tr>
<tr>
<td>Rancho Romero</td>
<td>KIA 39214</td>
<td>Ex situ charcoal</td>
<td>3975±30</td>
<td>4414±111</td>
<td>Active sedimentation</td>
<td>GE-9b</td>
</tr>
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<td>Rancho Romero</td>
<td>KIA 39212</td>
<td>Ex situ charcoal</td>
<td>3915±30</td>
<td>4335±87</td>
<td>Active sedimentation</td>
<td>GE-9b</td>
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<td>Rancho Romero</td>
<td>KIA 39213</td>
<td>Humic acid</td>
<td>3843±29</td>
<td>4279±126</td>
<td></td>
<td>GE-9c</td>
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<td>GE-11b</td>
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<td>Spinola</td>
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<td>9159±143</td>
<td>Soil formation</td>
<td>GE-5b</td>
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<td>Spinola</td>
<td>KIA 23950</td>
<td>Ex situ charcoal</td>
<td>2020±25</td>
<td>1969±72</td>
<td>Active sedimentation</td>
<td>GE-10</td>
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</table>

Guadalquivir River

<table>
<thead>
<tr>
<th>Profile</th>
<th>Lab no.</th>
<th>Material</th>
<th>$^{14}C$ age yrs BP</th>
<th>Cal. age BP (2σ)</th>
<th>Significance</th>
<th>Sed. unit</th>
</tr>
</thead>
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<td>Alcolea</td>
<td>Erl-15170</td>
<td>Ex situ charcoal</td>
<td>1812 ± 38</td>
<td>1742 ± 119</td>
<td>Start sedimentation</td>
<td>GQ-g</td>
</tr>
<tr>
<td>Alcolea</td>
<td>Erl-15171</td>
<td>Ex situ charcoal</td>
<td>4175 ± 63</td>
<td>4687 ± 157</td>
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<td>GQ-f</td>
</tr>
<tr>
<td>Alcolea</td>
<td>Erl-15172</td>
<td>Ex situ charcoal</td>
<td>4366 ± 34</td>
<td>4946 ± 92</td>
<td>Active sedimentation</td>
<td>GQ-e</td>
</tr>
<tr>
<td>Posadas</td>
<td>Erl-15173</td>
<td></td>
<td></td>
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4.4 Results

4.4.1 Stratigraphic findings of the Jarama River

4.4.1.1 Fluvial architecture

The floodplain of the lower Jarama Valley reaches a width of 3 km. Raised peripheral areas mark the location of late Pleistocene terrace remnants with a succession of about 8 m of fluvial sediments that are topped by alluvial fan material. This succession is covered by several layers of colluvial deposits that obliterate terrace steps towards the Holocene floodplain area. The Holocene floodplain occupies only a narrow area along the middle river course with river sediments being constantly rejuvenated due to repeated river erosion and sedimentation processes. In the lowermost river reach the Holocene floodplain widens and beside coarse grained channel deposits, early to late Holocene sediment successions were preserved (Fig. 4.2). Generally, sediments get younger from distal to proximal floodplain positions. In distal positions early to late Holocene sediments are stacked on top of one another. In proximal positions, where the active channel belt is located, older sediments have been eroded and, instead, thick layers of late Holocene sediments have been deposited. Youngest Holocene sediments are accumulated and eroded along both sides of the recent channel and build up small terrace bodies. One position approx. 3 km before the river mouth revealed that during the mid-Holocene the major part of the floodplain has been cleared out by river erosion before it was refilled with a mid- to late Holocene sediment succession (Fig. 4.2). Thus, the fluvial architecture of the lower Jarama River can be characterized as complex and inconsistent along specific river reaches.
Figure 4.2: Schematic sketch of the lower Jarama River fluvial architecture based on a number of 15 individual profile sections (see Figures 4.1 and 4.3). Sediment units are indicated together with sedimentation ages derived from radiocarbon dating. Note the different appearance of the cross sections with mid-Holocene sediments preserved in the rear section and late Holocene sediments in the front section.
4.4.1.2 Sedimentation patterns

About 14 different stratigraphic units have been identified, each of them comprising one or more sedimentary layers. Although hiatus as well as unconformities occur related to temporal interruptions of sedimentation and/or contemporaneous erosion processes, fluvial sedimentation history can be provided for a time span of the last 44 ka.

As a general observation (even if not applicable in every sequence), fluvial aggradation was realized multiple times in different periods according to the pattern – first gravel, followed by sands, followed by cohesive flood loams. Below is a summarized description of structure and composition of the sedimentary units together with a chronological resolution based on radiocarbon dating. For more detailed information see Wolf et al. (2013).

Late Pleistocene: A Late Pleistocene terrace body is mainly comprised of coarse and poorly sorted gravel (Fig. 4.2, unit JA-2) with an inner structure pointing to braided stream deposits. Radiocarbon dating revealed that the deposition of unit JA-2 started between 43,789±1502 and 37,972±768 cal. BP (Fig. 4.3, Tab. 4.1) and lasted until sometime between 19,193±254 and 16,493±898 cal. BP (Fig. 4.3, Tab. 4.1). In more proximal floodplain positions these gravels are regularly subject to strong deformation due to halokinetic activity of the underlying gypsum marls.

The following unit JA-3 represents a transitional stage from braided stream deposition towards the extensive deposition of reddish sandy loams. A charcoal from the middle of unit JA-3 yielded a radiocarbon age of 16,493±898 cal. BP (Fig. 4.3, Tab. 4.1). The subsequent accumulation of fine-laminated gypsum-bearing alluvial fans originating from framing marls (unit JA-4) started around 12,537±113 cal. BP (Holcim profile, Fig. 4.3 and Tab. 4.1) and indicates fine laminar washing processes.

Early to mid-Holocene: After a longer hiatus of sedimentation, Holocene floodplain aggradation started around ~7498±67 cal. BP (Fig. 4.2, Tab. 4.1) with the sedimentation of sands and sandy loams (unit JA-5). After a period without sedimentation, the apparently continuous accumulation of unit JA-7 took place from 5152±288 cal. BP until 3317±75 cal. BP (Fig. 4.3, Tab. 4.1). A priori raised contents of clay and organic carbon indicate strong contributions of relocated soil material (soil sediments). Another river section (Aranjuez profile, Fig. 4.1C) revealed different sedimentation patterns for the same period (Fig. 4.2). Here, above a distinct erosive surface within the Pleistocene gravel of unit JA-2, Holocene gravels (unit JA-6) were deposited with a multiple channel depositional pattern between 4284±126 cal. BP (waterlogged branch, Fig. 4.3, Tab. 4.1) and 3000 cal. BP (Figs. 4.2 and 4.3, Tab. 4.1). Unit JA-6 was then capped by clayey and sandy material that is regarded as waning flood deposit (unit JA-8).
Late Holocene: A homogeneous layer of unstructured loamy sands (unit JA-9) suggests a quick accumulation at around 2838±77 cal. BP (Fig. 4.3, Tab. 4.1) and is perhaps related to a fan-shaped crevasse splay in the lowermost river section. Thereafter, the sedimentary environment changed fundamentally and blackish clayey and humic flood loams (unit JA-10) were accumulated ubiquitously from shortly before...
2,120±171 cal. BP (Fig. 4.3, Tab. 4.1) until shortly after 1484±72 cal. BP (Fig. 4.3, Tab. 4.1) with a temporary disruption in between. These accumulations contain plenty of ceramics and artifacts as well as a certain proportion of gypsum (up to 17%), and thus give evidence for (1) human impact and (2) strong erosion of topsoil horizons within the surrounding gypsum marl landscape. Farther upstream, sediments of unit JA-10 cover Roman burial sites in close proximity to the Titulcia profile (Figs. 4.1C and 4.3) and during the same time colluvial layers filled and covered settlement pits in the surrounding of the Holcim profile (Figs. 4.2 and 4.3).

At least two more layers of humic flood loam have been deposited after 1484±72 cal. BP (JA-11 and JA-12 units, Fig. 4.2, Tab. 4.1) in distal floodplain positions. Unit JA-12 points to a deposition age of 423±90 cal. BP (Fig. 4.3, Tab. 4.1). Shortly after, around 385±89 ca. BP (Fig. 4.3, Tab. 4.1), exceptionally strong dynamics affected the floodplain and a reddish sandy material (unit JA-13) was deposited with a thickness of up to three meters in proximal positions and with a thickness of up to 0.5 m in distal positions pointing to planar sheet-like crevasse splay. A brown flood loam (unit JA-14) represents the top layer and refers to an accumulation until the recent past.

### 4.4.1.3 Periods of soil formation

Generally floodplain soils refer to periods of floodplain stability that are caused by lacking sediment influx or the decoupling of floodplain sections from active river dynamics. Nature and intensity of soil formation may be indicative for specific palaeoenvironmental conditions and/or exposure time. Most important characteristics of identified floodplain soils are summarized in Tab. 4.2. Comparing fossil topsoil horizons and related soil parent material for different time slots, the pedogenetic enrichment of organic matter is exceptionally low. However, as shown by Zielhofer et al. (2009) soil organic matter appears unsuitable to indicate soil maturity due to post-pedogenetic topsoil erosion and unfavorable preservation conditions under aerobic conditions. Likewise clay enrichment is difficult to interpret as sedimentary layers regularly appear as fining-upwards successions and pedogenetic clay is not separable from sedimentary clay without further analyses.

From a sedimentary point of view, the initial quantity of organic matter in fluvial sediments rose continuously with time. Especially for the last 2000 years a strong admixture of eroded soil material to fluvial sediments becomes apparent with organic contents of more than 0.3% and initial clay contents of more than 30% (Tab. 4.2).
Table 4.2 Characterization and estimated exposure duration of late Pleistocene and Holocene floodplain soils in the Jarama River floodplain. For time estimation see Table 4.1.

<table>
<thead>
<tr>
<th>Sed. unit</th>
<th>Maximum age of sed.</th>
<th>Minimum age of burial</th>
<th>Exposure time</th>
<th>Clay (%)</th>
<th>δ Clay (%)</th>
<th>Organic (%)</th>
<th>Munsell soil color</th>
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<td>JA-1</td>
<td>43,789±1502</td>
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<td>~5000</td>
<td>25</td>
<td>14.7</td>
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<td></td>
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<td>2,5 Y 5/2</td>
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<tr>
<td>JA-2</td>
<td>30,852±279</td>
<td>?</td>
<td>~4000</td>
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<td></td>
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<td>JA-3</td>
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<td>12,537±113</td>
<td>~2000</td>
<td>55</td>
<td>22.6</td>
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<tr>
<td>JA-7</td>
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<td>30</td>
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<td>JA-9</td>
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<td></td>
<td></td>
<td>10 YR 5/4</td>
</tr>
<tr>
<td>JA-10</td>
<td>&gt;2120±171</td>
<td>(1612±81)?</td>
<td>(~300)?</td>
<td>20</td>
<td>52.3</td>
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<tr>
<td>JA-11</td>
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<td>JA-11</td>
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<td>(~400)?</td>
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<td>10 YR 4/2</td>
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</tbody>
</table>

4.4.2 Stratigraphic findings of the Guadalete River

4.4.2.1 Fluvial architecture

According to heterogeneous sedimentation and sediment preservation patterns the valley of the lower Guadalete River is divided into two different sections, the lower and the upper downstream section. The upper downstream section (UDS) at a distance between 25 and 50 km from the coastline with a width between 0.5 and 1.5 km (Fig. 4.1D) refers to a juxtaposition of several sedimentary bodies related to repeated sediment accumulation and subsequent erosion (Fig. 4.4A). A late Pleistocene terrace body stretches along the valley margin with a mean elevation of 5 m above recent floodplain level. Approximately 25 km before reaching the coastline the terrace body gets buried by Holocene sediments (terrace crossing point) that mark the end of the UDS. In positions were the valley widens, late Pleistocene sediments are replaced by mid-Holocene sediments in more proximal positions, that in turn are replaced by late Holocene sediments nearby the recent river course.

In contrast, the lower downstream section (LDS) that extends over the last 25 km from the coastline (Fig. 4.1D) exhibits an architecture pointing to a floodplain widths of more than 2 km and large floodplain areas that are apparently untouched by fluvial erosion processes. Here, vertical aggradation of floodplain sediments dominated and river erosion was primarily restricted to the active channel-belt. Holocene terraces
Western Mediterranean environmental changes

Figure 4.4: A. Composite profile of the upper downstream section showing sediment units and most important $^{14}$C dating results. B. Composite profile of the lower downstream section. Cross sections are based on 18 individual profile sections and coring transects (see Figures 4.1 and 4.5).

are lacking and solely one continuous sediment succession (stack terrace texture) was built up ranging from early to late Holocene aggradations (Fig. 4.4B).
Moreover, when upper and lower downstream sections are compared, sediment units and deposition times are mainly not in line with each other. In the UDS mainly mid- to late Holocene sediments are preserved, whereas in the LDS likewise early Holocene sediments could be found.

4.4.2.2 Sedimentation patterns

A number of 15 sedimentary units have been identified along the lower Guadalete River floodplain. The availability of datable material permits a chronological resolution for a timeframe of the last 14 ka. The general stratigraphic configuration of the UDS indicates gravels at the base of the successions followed by sandy material and topped by flood loams. Since in the LDS channel activity was apparently restricted to a rather narrow channel-belt during Holocene, floodplain sedimentation in distal positions is characterized by a lack of gravel and alternating sandy and loamy deposits with a tendency towards fining-up sequences. For the purpose of a chronological sequence findings from the LDS and UDS are shown in summarized form. For more detailed explanations especially with regard to analytical data see Wolf et al. (2014).

Late Pleistocene: In the UDS, up to 4 m thick poorly sorted and strongly calcified gravels (unit GE-1) refer to a braided channel depositional pattern. Gravels remained in form of a fragmented terrace body on both fringes of the floodplain overlying Triassic and Tertiary marls (Fig. 4.4). The upper part of the terrace consists of sand and gravels (unit GE-2) and was strongly affected by weathering and rubefaction. Datable material is missing, solely late Phoenician / early Roman settlement pits that were directly inset into unit GE-2 give evidence for an exposure time until ~2.3 ka cal. BP. In the LDS, sediments of unit GE-1 and GE-2 are missing, but in a study carried out by Dabrio et al. (2000) in the Guadalete estuary just behind the recent coastline, a gravel layer was documented in a depth of 30 – 35 m, which we correlate with unit GE-1. Therefore, it appears likely that in the LDS, unit GE-1 already disappeared below the recent floodplain level and thus, was buried by Holocene floodplain sediments.

In the UDS, the depositional age of a channel fill (unit GE-3) points to 13,718±385 cal. BP (Fig. 4.4A, Tab. 4.1) giving evidence that the late Pleistocene terrace level was still influenced by active river processes during the Bølling and Allerød interstadials.

Early Holocene: Corresponding sediments are restricted to the LDS. According to ERT measurements (Wolf et al. 2014) basal Holocene sediments are composed of gravels (unit GE-4) that were buried in a depth between 9 and 15 m below ground level (Fig. 4.4B). After the subsequent sedimentation of several meters of sands (unit GE-5a) and sandy loams (unit GE-5b) a more or less stable floodplain surface existed until 8046±108 cal. BP (Fig. 4.5, Tab. 4.1). The floodplain was slightly affected by surface...
Figure 4.5: Selected key profiles from the Guadalete River system that are essential to comprehend the composite profile in Figure 4.4. For location see Figure 4.1. Dating is compiled in Table 4.1.

erosion before renewed sedimentation began around 7851±93 cal. BP (unit GE-6, Fig. 4.5) according to radiocarbon dating of mollusk shells.
Mid-Holocene: Periods of flood loam sedimentation recorded along the LDS range from 7851±93 to approximately 7000 cal. BP (unit GE-6) and from 6045±129 to 5568±83 cal. BP (unit GE-8) (Fig. 4.5, Tab. 4.1), followed by an aggradational period that affected likewise UDS and LDS. In the UDS, after strong river incision and erosion of older sediments, the accumulation of different gravel layers (unit GE-9a) began at about 4609±188 cal. BP (Fig. 4.4, Tab. 4.1) and refers to enhanced channel activity during that period. Sands and sandy loams (unit GE-9b) with depositional ages of 4414±111 and 4335±87 cal. BP (Fig. 4.5, Tab. 4.1) cover these gravels, although respective sediments have solely been found in protected floodplain positions of valley widening. In the LDS correlative sediments have been deposited until 3790±90 cal. BP (Fig. 4.5, Tab. 4.1) (units GE-9b and GE-9c). However, ultimately the resolution of dating does not permit a conclusive relation between upper and lower downstream sections and thus, deviating dynamics with out-of-phase sedimentation periods must be taken into consideration.

Late Holocene: In the UDS, organic-rich flood loams with high values for clay and iron contents (unit GE-10) were deposited since shortly before 1969±72 cal. BP and document the admixture of eroded topsoil material (Fig. 4.5, Tab. 4.1). It is likely that these flood loams are related to the deposition of blackish colluvial sediments on the late Pleistocene terrace level that buried settlement pits after 2245±93 cal. BP (Fig. 4.4, Tab. 4.1).

During the Medieval period, the incision of a network of up to 80 m wide secondary channels took place even in distal floodplain positions until 993±61 to 848±81 cal. BP (Fig. 4.4, Tab. 4.1), which have been refilled by humic and clay-rich substrates (unit GE-11b) originating from the Campiña de Cadiz marls. Simultaneously, gravels (unit GE-11a) and sands (unit GE-12) have been deposited in proximal positions (Tab. 4.1). A final strong dynamic impulse is visible during the Little Ice Age (LIA), when proximal floodplain positions were rapidly filled up with gravelly channel-bed deposits (unit GE-13a) and up to 3 m of fine laminated humic and organic-rich material (unit GE-13b) in a short time-span around 398±90 cal. BP (Fig. 4.5, Tab. 4.1). Similar sediments have been found in form of channel-fillings in the LDS as well. Flood loams of units GE-14 and GE-15 occur ubiquitously in both river sections and indicate modern sedimentations until the recent past (Figs. 4.4 and 4.5).

### 4.4.2.3 Periods of soil formation

Detected floodplain soils are briefly characterized in Tab. 4.3. The temporal resolution of soil formation periods is difficult due to the lack of appropriate datable material, thus estimated ages are indicated but should be treated with care. Strong pedogenesis was found on the late Pleistocene terrace surface (unit GE-1 and GE-2) that has been exposed during the majority of the Holocene. Further topsoil formation took place during the Bølling and Allerød interstadials at least in small floodplain depressions.
Western Mediterranean environmental changes

(unit GE-3). Long-lasting and intense soil formation was found in the LDS (unit GE-5) until 8046±108 cal. BP (Fig. 4.5, Tab. 4.3) that is likewise confirmed by analytical data. At least four more floodplain soils have been identified that were formed during the last 7000 years (Tab. 4.3) and that are mainly characterized by humic enrichment and mineral weathering leading to increased clay contents and stronger coloration caused by iron compounds. However, again pedological interpretation of clay contents should be done with caution (see section 4.4.1.3).

### Table 4.3 Characterization and estimated exposure duration of late Pleistocene and Holocene floodplain soils in the Guadalete River floodplain. For time estimation see Table 4.1.

<table>
<thead>
<tr>
<th>Sed. unit</th>
<th>Maximum age of sed.</th>
<th>Maximum age of burial</th>
<th>Exposure time</th>
<th>Soil horizon</th>
<th>Thickness [cm]</th>
<th>Clay (%)</th>
<th>δClay (%)</th>
<th>Organic (%)</th>
<th>δOrganic (%)</th>
<th>Munsell soil color</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE-2</td>
<td>&gt; 13,718±385</td>
<td>&lt;2234±35</td>
<td>?</td>
<td>Bw</td>
<td>60</td>
<td>19.2</td>
<td>-</td>
<td>0.29</td>
<td>-</td>
<td>Dark reddish brown</td>
</tr>
<tr>
<td>GE-3</td>
<td>13,718±385</td>
<td>?</td>
<td>Ah</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Dark brown</td>
</tr>
<tr>
<td>GE-5</td>
<td>7851±93</td>
<td>[- 2000]</td>
<td>C</td>
<td>80</td>
<td>50.2</td>
<td>11.4</td>
<td>0.39</td>
<td>0.17</td>
<td>10 YR 4/3</td>
<td>Dark brown</td>
</tr>
<tr>
<td>GE-6</td>
<td>&lt; 7851±93</td>
<td>[- 7000]</td>
<td>Ah</td>
<td>35</td>
<td>44.5</td>
<td>7.4</td>
<td>0.39</td>
<td>0.18</td>
<td>10 YR 4/3</td>
<td>Yellowish brown</td>
</tr>
<tr>
<td>GE-8</td>
<td>5568±83</td>
<td>&gt; 3788±87</td>
<td>Bw/C</td>
<td>35</td>
<td>44.1</td>
<td>10.5</td>
<td>0.59</td>
<td>0.27</td>
<td>10 YR 3/3</td>
<td>Dark brown</td>
</tr>
<tr>
<td>GE-9b</td>
<td>&lt;4279±128</td>
<td>&gt;3788±87</td>
<td>A/B</td>
<td>15</td>
<td>44.6</td>
<td>13.8</td>
<td>0.32</td>
<td>0.1</td>
<td>10 YR 5/4</td>
<td>Yellowish brown</td>
</tr>
<tr>
<td>GE-9c</td>
<td>~3788±87</td>
<td>~2200</td>
<td>A/B/C</td>
<td>20</td>
<td>40.6</td>
<td>6.1</td>
<td>0.46</td>
<td>0.14</td>
<td>10 YR 5/3</td>
<td>Yellowish brown</td>
</tr>
</tbody>
</table>

**4.4.3 Stratigraphic findings of the Guadalquivir River**

Two profile sections have been studied along the middle river section in the area surrounding Cordoba (Fig. 4.1B). Thus, stratigraphic findings are far away from being exhaustive but provide supplementary information on possible supra-regional dynamic patterns.

**4.4.3.1 Fluvial architecture**

The valley floor of the considered river section shows a width of about 2 to 3 km and is dominated by a terrace body of presumably late Pleistocene age with a surface level that is about 8 m higher than the recent river level. In the area of Posadas, the late Pleistocene terrace occupies nearly 80% of the valley bottom. At least two Holocene terrace steps were formed due to a progressive lowering of the active river floodplain. The recorded profile on the upper Holocene terrace indicates strong fluvial dynamics during the Mid-Holocene.
4.4.3.2 Sedimentation patterns

According to current information, 7 sedimentary units have been identified, giving insight into narrow time slots during the last 14 ka. Generally, gravels at the base of the units prove increased channel activity. The subsequent shift from coarse sandy material to cohesive flood loams indicates a change of dynamics and/or a changed availability of sediments.

**Late Pleistocene**: The late Pleistocene terrace refers to massive gravel deposits (unit GQ-a, Fig. 4.6) with exploration depths pointing to a minimum thickness of 6 m. Characteristic features are coarse and unsorted gravels in a grayish matrix in the lower part. The upper part is dominated by more reddish gravel layers with fine and cross-stratified gravels and intercalated sand layers that indicate stronger lateral shifting of involved river channels. Fine overbank sediments on top of the gravels (unit GQ-c) are generally less than 2 m thick. They have a sandy to silty character with reddish ochre-brown colors and are cemented by calcium carbonate in varying degrees. Occasionally, channels about 5 m deep and several tens of meters wide were found on the terrace level (Fig. 4.6) that were refilled by sandy to silty sediments (unit GQ-b). A slight soil formation becomes visible in the uppermost part that is finally topped by unit GQ-c. A radiocarbon dating of a charcoal at the base of such a channel-fill yielded an age of 13,531±210 cal. BP (Tab. 4.1) giving evidence for sedimentation dynamics during
Bølling and Allerød interstadials. Furthermore, it shows that the terrace surface was subject to active river processes during that time and incision took place later. Due to lacking datable material the time of terrace abandonment cannot be defined more closely at present state.

Mid-Holocene: Below mid-Holocene successions, abundant gravel deposits are present with alternating layers of coarse and fine gravels and individual sand lenses a few decimeters thick (unit GQ-d) (Fig. 4.7). Time and duration of gravel deposition remain unknown. At 4946±92 cal. BP (Tab. 4.1) the accumulation of 3 m of sandy material (unit GQ-e) began. Sediments are characterized by an alternate layering of pure ochre
sands and slightly clayey reddish sands; the latter are evidence for stronger weathering of the material (Fig. 4.7). Lacking indications of pedogenetic overprint point to continual sedimentation processes. An erosion unconformity overlain by fine to medium grained gravels reflects certain channel activity. In the following, the accumulation of less sandy and more humic and dark-brown material (unit GQ-f) until 4687±157 cal. BP (Tab. 4.1) indicates the incorporation of relocated soil sediment. According to age determination, accumulations of units GQ-e and GQ-f are summarized to one sedimentation period.

**Late Holocene:** The Late Holocene is characterized by a long lasting stability phase spanning almost three thousand years. During that time just moderate surface erosion affected the floodplain until new sedimentations set in shortly before 1742±119 cal. BP (Tab. 4.1, Fig. 4.7). Sediments are blackish, they show a humic and clayey character (unit GQ-g) and feature brick fragments and, among other things, a well-preserved Roman pottery (not shown). With respect to changed sediment characters a modified area of origin is expected. Most likely, this finding indicates an increased agricultural land-use in the Campiña de Cordoba marl-landscape under Roman occupation.

4.4.3.3 **Periods of soil formation**

Only little pedogenesis was found in the late Pleistocene succession (unit GQ-b) pointing to high clay- and low humic enrichment. Dating does not permit clear conclusions about time and duration of pedogenesis, but from a stratigraphic point of view it took place sometime after 13,531±210 cal. BP and sometime before a period of intense river incision.

A strong soil formation was observed in the upper mid-Holocene succession (in unit GQ-f) that is likewise confirmed by analytical data (Fig. 4.7). The dark brown and humic topsoil horizon with significant clay coating and a strong reddish brown subsoil horizon containing plenty of calcified pseudomycelia results from an exposure duration that lasted for about 3000 years.
4.5 Discussion

4.5.1 General view of fluvial architectural patterns as basis for interpretations

As a principal pattern, fluvial architecture in the examined river valleys was strongly modified with time. A progressive narrowing of the active floodplain went ahead with a reduction of accommodation space (Figs. 4.2 and 4.4A) and shallow but widespread accumulations from the early Holocene gave way to massive but spatially closely confined deposits in the latest Holocene. Accordingly, sedimentary environments were likewise altered and sedimentation conditions are hardly comparable throughout the late Pleistocene and Holocene. Moreover, moderate and long-lasting sedimentation phases are contrasted by brief and vigorous accumulations. This means that a number of indicators that are usually used in fluvial archive studies, like sedimentation rates, palaeo-magnetic and environmental-magnetic values, the number of charcoal pieces or geochemical distributions can only be applied to a limited degree. Ultimately, suitable data are limited to fluvial sedimentary units that may be interpreted in terms of sedimentary environments (e.g. Richards 1988, Nanson and Croke 1992) and that, if chronologically resolved, give evidence for certain time periods of floodplain sedimentation, floodplain stability, and in some cases floodplain erosion.

A particular situation exists where adjacent parts of the river valley show diverging sedimentation patterns as e.g. discussed by Schumm (1973 & 1979). Here, a basic requirement for appropriate interpretations is to link particular sediment strata to certain deposition processes (Miall 1985, Houben 2007). Consequently, we found that uneven floodplain developments can mostly be attributed to the distance of accumulation sites from active channel positions. This is exemplified by the Jarama valley where a simultaneous sedimentation of cohesive flood loams in distal floodplain positions (unit JA-7) and coarse grained channel-bed facies in more proximal positions (unit JA-6) took place (see Wolf et al. 2013), demonstrating that the contemporary accumulation of different deposits in different floodplain positions was controlled by varying channel and discharge patterns.

4.5.2 Fluvial dynamic patterns and possible forcing mechanisms

According to stratigraphic findings, following general dynamic phases of floodplain activity (i.e. sedimentation) and floodplain stability (i.e. soil formation) can be designated.

(1) In the lower Jarama River valley floodplain sedimentation was observed ~40–18, around 16.5 and 7.5, 5.1–3.3, at 2.8, 2.1–1.5, around 1.0, and from 0.4 ka cal. BP until recent times. Phases of soil formation were detected around 43 and 31, 16–12.6, after 7.5 until 5.1, 2.8–2.1 and at times after 1.5 ka cal. BP.
Western Mediterranean environmental changes

In the lower Guadalete River valley floodplain sedimentation took place around 10, after 7.9, at 6.1–5.5 and 4.6–3.8, around 2.0, at 1.1–0.8 and since 0.4 ka cal. BP, while soil formation was found during the Bolling and Allerød interstadials, prior to 8.0 and 6.1, and at 5.5–4.6, 3.7–2.3, 1.9–1.1 and 0.7–0.4 ka cal. BP.

First results obtained for the lower Guadalquivir River give indications on floodplain sedimentation around 13.5, between 5.0 and 4.6, and after 1.8 ka cal. BP, as well on soil formation between 4.6 and 1.8 ka cal. BP.

It is well known that fluvial dynamics are controlled by external factors, such as climate, tectonics, base-level changes and anthropogenic impact, but likewise by intrinsic forcing. Accordingly the studied river systems reveal individual sedimentation histories dependant on the respective influence of all these different factors. For instance, the impact of sea-level changes may be neglected for the Jarama catchment that is situated in central Spain, but the case is different for the Guadalete and Guadalquivir rivers that discharge directly into the Gulf of Cádiz. These rivers have been strongly affected by sea-level drops (e.g. incision during Last Glacial Maximum and Younger Dryas in Guadalete and Odiel / Tinto estuaries, see Hernández-Molina et al. 1994, Dabrio et al. 2000, Lobo et al. 2002) as evidenced by times of terrace abandonment (e.g. Fig. 4.4, see Wolf et al. 2014), as well as by subsequent sea-level rises (see e.g. Goy et al. 1996, Blum and Törnqvist 2000, Dabrio et al. 2000, Vis et al. 2008). Likewise tectonics may play a pivotal role related to amount and rate of sedimentation and incision processes. Since all study areas are located in tectonically active mountain forelands and are characterized by vast deposits of evaporitic marls within the catchments, a strong tendency to deformation in terms of halokinetic deformation such as diapirism and subrosion structures as well as the formation of weak zones along fault lines may appear (e.g. Rodríguez Vidal et al. 1993, Gutiérrez et al. 2002, Luzón et al. 2008, Silva et al. 2013). Detailed discussions of the significance of tectonics and base-level changes for fluvial dynamics are provided in Wolf et al. (2013) for the Jarama River system and Wolf et al. (2014) for the Guadalete River system.

In order to get further insights into possible forcing mechanisms on fluvial dynamics, findings were compared with data from hydrology-sensitive and climate-sensitive environmental archives (Fletcher and Sánchez Goñi 2008, López-Merino et al. 2012) that were primarily pollen studies and lake records (Figs. 4.8 and 4.9). Given the distinct regionality of environmental conditions in Iberia, each catchment was addressed separately and solely records of strong regional context were chosen for comparison (see map in Fig. 4.9). Generally, results show a clear picture of high percentages of mesophytic vegetation and lower percentages of xerophytic vegetation during periods of floodplain stability and opposed to that, declines in mesophytes and higher percentages in xerophytes in line with periods of floodplain aggradations. Additionally, floodplain aggradations are apparently linked to lake desiccation phases. Moreover, information was added to Figs. 4.8 and 4.9
Figure 4.8: Summary of late Pleistocene and Holocene Jarama River floodplain dynamics and related sedimentary features together with a compilation of palaeoecological records providing information of regional relevance. (a): Phases of fluvial sedimentation (red bars) and floodplain stability with soil formation (green bars) for the last 14 ka. Temporal uncertainties are indicated by question marks. (b): Background data for time control of sedimentation history. (c): Characterization of sediments including sediment texture (S...sand, U...silt, C...clay, L...loam) and sediment color (black: blackish and humic flood loam, brown: brownish sediments, white: greyish laminated sediments). (d): Position of cultural remains like bricks and ceramics within floodplain sediments. (e): Pollen percentage record of Mesophytes, Xerophytes, Pseudoschizaea indicating lake desiccation and anthropogenic indicators from lake Siles, south-central Spain (Carrió 2002). (f): Pollen percentage record of Steppe taxa from Sierra de Cebollera, north-central Spain (Gil García et al. 2002). (g): Pollen percentage record of arboreal trees from Ambliés Valley peat bog, central Spain (López-Sáez et al. 2009). (h): Pollen percentage record of Xerophytes and Mesophytes from Villaverde, south-central Spain (Carrió 2002). (i): Benthic diatoms record pointing to arid phases and pollen percentage record of Arboreal trees and land use indicators from Somolinos Lake, central Spain (Cúrrás et al. 2012). (j), (k): Suggestion of possible climate forcing of floodplain dynamics based on a comparison of own findings with palaeoecological records. (l): Suggestion of possible anthropogenic contribution to floodplain sedimentation based on sediment character.

Concerning kind and character of fluvial sediments and traces of human impact (Figs. 4.8 (c)-(d) and 9 (o)-(p)) in order to estimate a possible anthropogenic influence on floodplain dynamics. The idea is that the occurrence of blackish and clayey sediments may be indicative of accelerated topsoil erosion due to forest clearance and farming activities in the catchment (e.g. unit JA-10 in Fig. 4.3 or unit GQ-g in Fig. 4.7). Consequently, it emerges that serious anthropogenic influence on the environment was apparently not exerted before 2.3 ka cal. BP that is likewise confirmed by numerous other studies on the Iberian Peninsula (e.g. Jalut et al. 2009, Roberts et al. 2011).
Figure 4.9: Summary of late Pleistocene and Holocene Guadalete River floodplain dynamics and related sedimentary features together with a compilation of palaeoecological records providing information of regional relevance. (m): Phases of fluvial sedimentation (red bars), fluvial incision (black bars) and floodplain stability with soil formation (green bars) for the last 14 ka. Temporal uncertainties are indicated by question marks. (n): Background data for time control of sedimentation history. (o): Characterization of sediments including sediment texture (S...sand, U...silt, C...clay, L...loam) and sediment color (black: blackish and humic flood loam, brown: brownish sediments). (p): Position of cultural remains like bricks and ceramics within floodplain sediments. (q): Lake level changes and desiccation events Laguna de Medina, south-western Spain (Reed et al. 2001). (r): Pollen percentage record of Xerophytes and Quercus forest from lower Guadiana Valley, southern Portugal (Fletcher et al. 2007). (s): Lake level changes Zoñar Lake, southern Spain (Martín-Puertas et al. 2009). (t), (u): Suggestion of possible climate forcing of floodplain dynamics based on a comparison of own findings with palaeoecological records. (v): Suggestion of possible anthropogenic contribution to floodplain sedimentation based on sediment character.
4.5.3 The role of climate in triggering fluvial dynamics

Cohesive floodplain sediments are not only indicative for particular hydrologic conditions that result in a series of more or less extreme flood events, but furthermore their composition allows conclusions to be drawn concerning the origin of sediments and the conditions under which these materials have been mobilized. In general, extensive accumulations of cohesive floodplain sediments are indicative for substantial soil erosion processes within the catchment that enable the mobilization of larger sediment quantities. Such circumstances are usually related to fragile landscape systems (Fletcher and Zielhofer 2013) by means of a deteriorated resilience of ecosystems to certain factors. For instance, it has amply been documented that the accumulation of cohesive floodplain sediments increased strongly with the increase of human-induced soil erosion processes especially during the late Holocene (Dotterweich 2008, Hoffmann et al. 2009, Dusar et al. 2012). Apart from anthropogenic pressure, increased fragility may be caused by changes in the hydrological system. In case of semi-humid and semi-arid Iberia, increasing aridity may exert influence on the landscape through lowering of the soil moisture content and disturbances of the vegetation systems (diminished vegetation cover with partly bare soils; Desprat et al. 2003, Eybergen and Imeson 1989, Vicente-Serrano et al. 2006, Ruiz-Sinoga and Romero Diaz 2010) and via accentuated precipitation patterns with heavy rainfalls that, together, produce higher runoff and erosion of soil material (Blum and Törnqvist 2000, Lavee et al. 1998, Walling and Kleo 1979). For example, Ruiz-Sinoga and Romero Diaz (2010) suggest a soil degradation threshold that is defined by an average annual rainfall, below which soil degradation is intensified related to changing vegetation composition. The principle of this statement describes a regularity that has been addressed by Langbein and Schumm (1958), who described the relation between sediment yield and annual precipitation dependant on vegetation density that is adjusted to rainfall and the hydrologic regime associated therewith. Consequently, in a more or less natural system, a climate change towards more arid conditions that exceeds a certain threshold of adaptability of vegetation, initiates higher erosion rates and thus, a higher sediment yield to the drainage system (geomorphic threshold, see Schumm 1979). Dependant on scope and extent of processes, sediments will reach depositional sites in floodplain positions (Imeson and Lavee 1998, Faust and Schmidt 2009). Reversely, periods of intense floodplain sedimentation may be indicative for a particular soil-water-vegetation-erosional system (Lavee et al. 1998) which arises particularly from climatic aridification.

Considering the above mentioned comparison with pollen archives and lake records (section 4.5.2), we suggest a correlation between climatic aridification and periods of catchment erosion and floodplain aggradation (Figs. 4.8 (j) and 4.9 (t)) (rhexistasy after Erhart 1955) as well as more humid climate conditions and floodplain stability including soil formation and lacking sediment input (Figs. 4.8 (k) and 4.9 (u)) (biostasy after Erhart 1955).
In addition, as Figs. 4.8 and 4.9 reveal, late Holocene sedimentation periods that correspond to climatic aridification phases bear likewise signs of anthropogenic degradation (Figs. 4.8 (l) and 4.9 (v)). Due to certain limits of the explanatory power of sedimentary archives (see e.g. Dusar et al. 2012), the role of human impact can actually not be considered separately from climate forcing, but we assume that the temporal coincidence of human land use and climatic aridification not only caused, but also reinforced sediment mobilization and subsequent floodplain sedimentation (see also Faust et al. 2004, Roberts et al. 2011, Wolf et al. 2013).

4.5.4 Supra regional comparison of examined floodplain records

A comparison of the different floodplain records is intended in order to review the presence of supra regional effective factors. It is suggested, that conformity of floodplain sedimentation or floodplain stability in at least two of the studied areas might be indicative for supra regional forcing, likely in the form of environmental and climatic conditions. Nevertheless, every river catchment possesses a unique individuality regarding physiographic composition, and sensitivity towards a wide range of possible influencing factors may considerably change between regions. Keeping that in mind, deviating patterns are considered as representing regional or local peculiarities, e.g. due to tectonic forcing, regional climate or human impact.

Fluvial dynamic patterns of the three studied river systems are compared in Fig. 4.10, with red bars indicating floodplain sedimentation, green bars indicating floodplain stability with lacking sedimentation and dark grey bars indicating strong floodplain incision and erosion of sediments. Following correlations arise from that comparison. Periods of sedimentation in at least two catchments appeared 8–7 ka, 5–3.8 ka, 2.2–1.5 ka, around 1 ka and at 0.4 ka cal. BP. Periods of supra regional floodplain stability and soil formation appeared 13.3–12.7 ka, 7–5.1 ka (with a short interruption around 6 to 5.5 ka), 2.8–2.3 ka, 1.4–1.2 ka and 0.8–0.5 ka cal. BP (see also Tabs. 4.2 and 4.3). A period of strong incision and erosion within two river systems took place during the Younger Dryas between 12.7 and 11.5 ka ca. BP. All deviating dynamics are seen as just regional patterns and are discussed separately.

Based on the findings shown in Fig. 4.8 (j)-(k) and Fig. 4.9 (t)-(u) a column was added to Fig. 4.10 (d) providing information on the relation between periods of supra regional effective floodplain dynamics and the hydrological conditions in all the catchments. Following this, supra regional floodplain aggradations are principally related to arid climate conditions, especially from 8 to ~7.3, from ~5.1 to ~4.8, from 2.2 to 1.9 and at ~0.4 ka cal. BP. Furthermore the sedimentation period between 1 and 0.8 ka cal. BP seems to be linked to aridity (Martín-Puertas et al. 2010, Moreno et al. 2012), although the matter is not beyond doubt. Phases from 13.6 to 12.8, from ~7 to 5.1 and from 2.7 to 2.2 ka cal. BP indicate supra regional floodplain stability coinciding with increased humidity, except for a short aggradation interval between 6.1 and 5.5 ka cal. BP in the
4 Western Mediterranean environmental changes
4 Western Mediterranean environmental changes

Figure 4.10: Summary of late Pleistocene and Holocene floodplain dynamics in three studied Atlantic river basins and a correlation with information derived from marine corings as well as from further fluvial records in the Western Mediterranean. (a)-(c): Succession of late Pleistocene and Holocene fluvial dynamics of (a) the Guadalete River floodplain, (b) the Jarama River floodplain and (c) the Guadalquivir River floodplain. Temporal uncertainties are indicated by question marks. (d): Climate forcing of fluvial dynamics in a supraregional context as derived from Figs. 9 and 10 with yellow bars indicating arid conditions and green bars indicating humid conditions. (e): Designation of phases of landscape evolution according to fluvial dynamic periods. (f): SST reconstruction curve of a marine coring in the Western North Atlantic (LO09-14) (Berner et al., 2008). (g)-(i): SST reconstruction curves of marine corings at the North Atlantic Iberian margin (g) SU8118 (Bard et al., 2000), (h) MD95-2040 (Pailler and Bard, 2002) and (i) MD95-2042 (Pailler and Bard, 2002). (j): SST reconstruction curve of the North Atlantic Iberian margin (MD95-2042) (Chabaud et al., 2014). (k): Pollen percentage record of Mediterranean forest from the marine sediment core MD95-2042 at the North Atlantic Iberian margin (Chabaud et al., 2014). (l): Sedimentation rates in mm/year for the Mid-Medjerda floodplain in Northern Tunisia (Zielhofer et al., 2008). (m): Probability plot of flooding episodes in Spain (Macklin et al., 2006). (n): Alluviation periods in the Bardenales National Park in Northeastern Spain (Sancho et al., 2008).

Guadalete floodplain (Fig. 4.9). A special situation is documented during the Younger Dryas between 12.6 and 11.6 ka cal. BP, when intense river incision and erosion took place in the Guadalete and Guadalquivir floodplains, meanwhile alluvial fan formation was realized in the Jarama Valley. Most likely these dynamics stand in relation to cold and arid climate conditions (Bateman and Herrero, 1999, Dorado Valiño et al., 2002, Fletcher et al., 2007, Gil Garcia et al., 2002, Vegas et al., 2010), but certainly incision along the Guadalete River has been supported by sea-level fall.

4.5.5 Variability of fluvial dynamics: A matter of sensitivity?

When comparing the examined river catchments, differences in fluvial dynamics on a supra-regional scale are reflected in (i) time delay in onset and/or offset of dynamics, as obvious between 5.1 and 3.2 or between 2.3 and 1.4 ka cal. BP (Fig. 4.10 (a)-(c)), (ii) differing duration of specific dynamics, or (iii) opposing dynamics like during the Younger Dryas, between 6 and 5.5 and around 2.8 ka cal. BP. Such differences may relate to a different geographic scope of determining factors, such as different regional climate patterns. Alternatively, the sensitivity of a river basin to external influences may be responsible for a varying response of individual river systems. In this context, the initial precipitation regime appears crucial in order to assess the way in which a specific eco-system will react to climate changes. In accordance with the concept of Langbein and Schumm (1958), eco-systems might react on climatic aridification in different ways depending on the initial state of hydrological conditions. With a higher initial moisture availability related to higher and more constant precipitation, incipient aridity will lead to declining vegetation cover and this in turn will induce progressive environmental pressure. Based on the principle of geomorphic thresholds (Schumm 1979), the geomorphological system will respond with delay (see also Knox 1972). Starting from an a priori less resilient environment, linked to more arid climate conditions with low
annual precipitation, increasing aridification will produce immediate effects resulting in a fast geomorphic response. For example, the pronounced climatic aridification starting at about 5 ka cal. BP (see Aranbarri et al. 2014, Bellin et al. 2013, Carrión et al. 2010, Jalut et al. 2009, Pérez-Obiol et al. 2011) caused floodplain aggradations within all the studied river systems, although with varying onset times and durations (Fig. 4.10 (a)-(c)). Based upon previous considerations, and provided that even in former times comparable relative hydrological differences have been existent between the river catchments, the Jarama catchment with comparatively continental and dry preconditions may have shown a faster response on progressive aridification than the Guadalete catchment with more humid preconditions and, thus a higher buffer capacity. Likewise the duration of geomorphological activity may depend strongly on initial hydrological conditions. For example, Walling and Kleo (1979) suggest an up to four times higher recovery time after disturbances in semi-arid compared to humid areas (see also Harvey 2007). This aspect may have been responsible for the short recovery times of the Guadalete and Guadalquivir systems and the long-lasting landscape instability of the Jarama system.

A comparable circumstance could be accounted for the vigorous floodplain sedimentations of the Jarama around 2.8 ka cal. BP that may demonstrate landscape response to an abrupt climate change. As mentioned in Wolf et al. (2013), numerous archives in central Spain revealed a transition from arid to humid conditions between 2.9 and 2.6 ka cal. BP (e.g. Carrión 2002, Currás et al. 2012) that fits well with a North Atlantic cooling period (Berner et al. 2009, Bond et al. 1997, van Geel et al. 1997). Initial aridity may have caused a state of increased fragility. The rapid change towards more precipitation and higher runoff would have initiated enhanced erosion dynamics until the recovery of vegetation led to renewed stability (see also Knox 1972, Törnqvist 2007). As no floodplain aggradations were found in southwestern Spain (Fig. 4.10), we suggest that higher initial humidity provided favorable conditions for an abundant vegetation cover (higher buffer capacity) that in turn prevented from geomorphological system reaction. The corresponding interaction of climate, vegetation and erosion systems during the Mid-Holocene aridification and the 2.8 ka event is exemplarily shown in Fig. 4.11 for the Jarama catchment, based on the conceptual model of Knox (1972).

When dealing with the issue of buffer capacity likewise the catchment size of river basins might be an important parameter (De Vente et al. 2007, Schumm 1991). A larger dendritic drainage network will be associated with a larger number of sedimentary sinks and thus a higher capacity for temporary sediment storage. That, in turn, may result in a delay of sediment transfer to the lower river course (Törnqvist 2007). This argument might, for example, be used to explain the Guadalete system showing a faster geomorphic response to the aridity period that started at around 2.1 ka cal. BP (Martín-Puertas et al. 2008) compared to the much larger Guadalquivir system. However, as the order of system response during Mid-Holocene was exactly the opposite (Fig. 4.10 (a)-(c)) perhaps other factors such as, for example, different times of
cultivation of the highly erodible marl landscapes within the catchment (e.g. Willms 1997) may be responsible for different times of sedimentation.

In the end, there is usually more than one possibility to provide explanation attempts for specific landscape dynamics, but we have to admit that there is a general risk to oversimplify or misinterpret complex relationships. In dealing with geomorphological processes, causes and effects are manifold and sometimes even hard to reconstruct, especially in the context of man-environment interrelations. In order to achieve substantial progress on this issue, more intensive research is required on terrestrial archives that reflect geomorphological activity on different spatial scales. The higher the spatial density of archive studies, the more likely it is to keep up with the spatial variability of influencing parameters and to approximate actual causal relationships. Moreover, the temporal resolution of very different archives still poses an obstacle in order to address issues like system response, buffer capacities and delay effects in detail.

4.5.6 Large-scale consideration of Western Mediterranean fluvial records

Further studies on fluvial archives in the Western Mediterranean were chosen to verify whether there is conformity of fluvial dynamics beyond central and southwestern Spain (Fig. 4.10). In fact, fluvial archives are still underrepresented considering the large
amount of terrestrial archive studies in the Western Mediterranean. However, remarkable consistency exists between fluvial records in Spain and northern Tunisia (Zielhofer et al. 2008), at least from 5.5 ka cal. BP (Fig. 4.10 (l)) and apart from some deviating dynamics at around 2 and 0.7 ka cal. BP. Zielhofer et al. (2008) observed that Tunisian alluvial archives exhibit phases of increased fluvial dynamics under generally drier conditions, which basically supports our findings (section 4.5.3). Furthermore, it has been shown that periods of fluvial activity in Tunisia match well with North Atlantic coolings, although precipitation patterns seem to be more closely related to autogenic Mediterranean depressions.

In turn, the fluvial record studied by Sancho et al. (2008) in the semi-arid northeastern Spain shows predominantly non-conform dynamics compared to central and southwestern Spain (Fig. 4.10 (n)). Likewise records within the upper and lower Guadalentín Basin (Silva et al. 2008, Baartman et al. 2011) or the Vera and Sorbas Basins (Schulte 2002) in the semi-arid southeastern Spain show a low level of consistency. There may be a number of reasons for that, e.g. Baartman et al. (2011) suggest that within the Guadalentín Basin internal dynamics as well as tectonic impact superimposed climate forcing resulting in a very heterogeneous pattern of fluvial dynamics even within the same catchment.

Due to the fact that the Betic Mountain Ranges act like a barrier against moist air masses approaching with the main direction of circulation from the Atlantic Ocean, most areas in semi-arid southeastern Spain point to mean annual precipitation below 300 mm (Schulte 2002, Silva et al. 2008) and natural vegetation is mainly characterized by steppe (Lautensach 1964). Such eco-systems are particularly vulnerable to denudation processes (Langbein and Schumm 1958), as precipitation shows maximal geomorphological efficiency, especially in view of local extreme rainfall originating from autogenic depressions along the Mediterranean coast. This may result in spatially and temporally heterogeneous patterns of landscape degradation that apparently prevent from the development of similar fluvial dynamic patterns in SE-Spain, and all the more when considering entire Spain. Based on this information, probability plots of flooding episodes covering whole Spain as e.g. shown by Macklin et al. (2006) (Fig. 4.10 (n)) may not always be easy to interpret. As obvious in Fig. 4.10, there are of course coincidences between peaks of the probability plot and flooding periods detected in the Jarama and Guadalete systems, but as the plot includes flood records across total Spain, all spatial information of flooding activity get lost. However, if for example SWD-records (slack water deposits) that are indicative for extreme flood events are taken from a regional context and compared to floodplain records (Fig. 4.12) there may arise valuable hints concerning the consistency of periods of floodplain aggradation and extreme flood events that fits well with the concept derived in section 4.5.3.

Further examination is needed on whether a correlation can be established with the more humid northwestern Spain that already belongs to the west wind zone of the temperate latitudes.
Figure 4.12: Compilation of palaeo-flood information containing a floodplain record of the Jarama River (this study), a SWD-record (slack water deposits) of the Tajo River (Benito et al. 2003) and a historical flood record of the Jarama River (Uribelarrea et al. 2003).

4.5.7 Interrelations between North Atlantic sea surface temperature and landscape dynamics on the Iberian Peninsula

Given the close relationship between landscape evolution and climate conditions on regional or catchment scale (Figs. 4.8 and 4.9), the question arises whether there are linkages to large-scale climate patterns. For this purpose different records indicating late Pleistocene and Holocene North Atlantic sea surface temperatures (SST) are shown in Fig. 4.10 (f)-(j). Apart from partly divergent trends of different SST curves (e.g. Fig. 4.10 (f) and (i)) that may be due to a certain regionalism of hydrographical trends in the North Atlantic Basin (de Vernal and Hillaire-Marcel 2006, Morley et al. 2014) there is a general coincidence of fluvial sedimentation periods in Spain and North Atlantic cooling. Furthermore, Chabaud et al. (2014) reconstructed SST and pollen percentages of the same marine core (MD95-2042) on the Iberian Margin off Lisbon (Fig. 4.10 (j)-(k)) and suggest that cooler SSTs went along with forest declines and more arid conditions over SW-Iberia. As marine pollen assemblages appear to give an integrated image of vegetation composition on the adjacent continent (Naughton et al. 2007) we tend to interrelate SST decreases and Mediterranean forest declines with continental aridity and related landscape instability (Fig. 4.10 (d), yellow boxes), as happened during the Younger Dryas, the Early- to Mid-Holocene aridification, the Mid-Holocene aridity collapse and the Roman crises (Fig. 4.10). Reversely, periods of landscape stability (Fig. 4.10 (d), green boxes) are mainly accompanied by increased SSTs and higher percentages of Mediterranean forest pollen. Even for the last glacial Moreno et al. (2005) observed a convincing parallelism of SST decreases and steppic vegetation growth during Dansgaard / Oeschger stadials with associated North Atlantic Heinrich Events in the Alboran Sea. They argue that during Pleistocene, cooling of the subpolar North Atlantic was accompanied by an enhanced SST and pressure gradient in the North Atlantic, stronger north-westerly wind over the north-western Mediterranean, and thus higher continental aridity.

4.5.8 Landscape dynamics and corresponding atmospheric conditions

Following Fletcher and Zielhofer (2013) the precise climatic conditions that are responsible for the generation of high flood events are still under debate. Following the results shown in section 4.5.3, we suggest that under more humid conditions with a
generally increased moisture level, extreme rainfall events may be significantly buffered by higher infiltration capacities of the soils (Faust 2003) as well as the protective character of stable and intact ecosystems. This is not to say, of course, that runoff accumulation and flooding fail to occur. But in case of landscape destabilization and diminished vegetation cover due to highly variable monthly rainfall, extreme precipitation events are of much more erosive nature and tend to high geomorphological effectiveness (see also Langbein and Schumm 1958, Faust & Schmidt 2009). Therefore, it might be considered that flooding periods that are recorded in floodplain records of southwestern and central Spain may be indicative for more arid environments, rather than for humid ones.

It is generally accepted that landscape aridity is characterized by a decrease of rainfall frequency and an increase in rainfall intensity (Bullón 2011, Lavee et al. 1998). Corresponding circulation patterns might include a bypassing of cyclones during winter, for instance due to a northward shift of the westerly belt. The concept of North Atlantic SST cooling together with enhanced North Atlantic pressure gradient leading to a stronger west wind drift appears particularly suitable to explain increased aridity over large parts of the Iberian Peninsula. Resulting moisture deficit transfers landscapes into fragile conditions and highly variable and intense precipitation may foster catchment erosion and fluvial sedimentation processes.

### 4.6 Conclusion

This study presents a comprehensive research on fluvial sedimentation history for the last 14 ka in different catchments in Spain. Extensive work in the Jarama and Guadalquivir River Basins is complemented by first results from the Guadalete River Basins. Generally, it has been shown that river floodplains on the Iberian Peninsula feature a very complex fluvial architecture. Therefore, in order to meet this complexity, it is essential to study a large number of profile sections in different floodplain positions. In a further step, we deduce that floodplain dynamics in lower river reaches with large catchment areas may be reflective for the most significant landscape developments across the whole catchment. Important findings are:

1. For each river catchment striking periods of geomorphological activity as well as stability have been elaborated, with activity periods regularly being linked to floodplain aggradations, and stability periods being accompanied by soil formation and lacking sedimentation, but likewise river bank erosion due to river meandering.

2. Different factors have been identified that influence fluvial dynamics, however, in a comparison with palaeoenvironmental and palaeoclimatic archives on regional or catchment scale it became obvious that decisive control may be exerted by climate.
Furthermore, flooding periods associated with floodplain aggradations seem to be related to arid climate conditions, and periods without flooding and with associated floodplain soil formation seem to be related to more humid climate conditions.

The different river systems show consistent dynamics for certain time periods, which means that there is a supra regional reaction of landscapes on climate fluctuations across central and southwestern Spain.

However, there are likewise deviating patterns like divergent onset and/or offset of dynamics, differing duration of dynamics, or even opposing dynamics that may be due to regional climate variability or other factors of local or regional relevance. Apart from tectonic impact or base-level changes, considerable influence may originate from the buffer capacity of a catchment to climatic influences and associated thresholds for the activation of geomorphological systems. The buffer capacity appears to be strongly dependent on initial hydrological conditions that control vegetation cover, on the respective type of climate change (dry to humid vs. humid to dry, fast vs. slowly) as well as on catchment size.

It turned out that there is a strong regional aspect concerning fluvial dynamics and landscape evolution in general. Even if dynamics of the river systems addressed in this study are relatively similar, the comparison with other Western Mediterranean regions like SE-Spain that is little affected by Atlantic cyclones unveils that according to strong climatic differences likewise geomorphological systems show very different patterns. Therefore, if it is intended to examine large-scale fluvial dynamic patterns or even a connection to global climate fluctuations, included river systems should be selected cautiously given the heterogeneous physiographic setting of most river basins. However, also when other archive information is correlated, the necessary caution related to the spatial relevance of the examined values should be exercised.

When results are compared with information from North Atlantic marine coring, a certain coincidence between North Atlantic coolings, more arid climate conditions over Iberia, and increased landscape dynamics in terms of catchment erosion and floodplain sedimentation appears. By contrast, North Atlantic warm periods tend to be linked with more humid climate conditions as well as stability and preservation within the river basins.

Appreciable human influence is perceivable since 2.3 ka cal. BP based on fluvial sediment characteristics. However, both human impact and climatic aridification have the potential to destabilize landscape systems, therefore mono-causal interrelations may not be possible to specify. Probably, increasing pressure of exploitation converted landscapes into more fragile conditions that enabled hydrological events to achieve greater geomorphological effects.

Ultimately, fluvial archives seem to be exceptionally well suited for studying landscape evolution over longer periods of time. In-depth comparisons with other archive studies...
are, however, indispensable in order to recognize interrelations between climate, vegetation and geomorphological systems. Future research should give closer attention on fluvial archive studies to reveal large-scale relations while still meeting the spatial variability of landscape dynamics.

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References


4 Western Mediterranean environmental changes


Dorado Valiño, M., Valdeolmillos Rodriguez, A., Blanca Ruiz Zapata, M., José Gil García, M., de Bustamante Gutiérrez, I., 2002. Climatic changes since the Late-glacial/Holocene transition in La Mancha Plain (South-central Iberian Peninsula, Spain) and their incidence on Las Tablas de Daimiel marshlands. Quaternary International 93-94, 73–84.


Fletcher, W.J., Boski, T., Moura, D., 2007. Palynological evidence for environmental and climatic change in the lower Guadiana valley, Portugal, during the last 13 000 years. The Holocene 17, 481–494.


5 Synthesis

5.1 General architectural patterns of examined river floodplains in Spain

In view of the extensive results that were obtained from floodplain sediments of various river systems, certain basic conclusions related to the fluvial architecture of Atlantic river basins in Spain may be drawn. In general, the examined rivers show a highly dynamic runoff regime that can be related to high mean river gradients and short distances to framing mountain ranges. In contrast to river basins with a tendency to subsidence and thus sediment preservation (e.g. Zielhofer and Faust 2008), rivers in Spain are rather affected by fluvial erosion, i.e. principally river bank erosion. Unlike a homogeneous deposition of sediment successions, these river systems are characterized by recurrent phases of sedimentation and erosion that causes the clearing out of sediment units and the rejuvenation of sediment successions from distal to proximal floodplain positions. Individual sediment units may occur side by side, one upon the other, or nested within each other.

Generally, a late Pleistocene terrace body that usually extends over large parts of the valley bottom frames the active floodplain (chapters 3.4.1 and 4.4). This terrace is mainly composed of large unsorted gravels and points towards braided style runoff patterns during certain periods of the last glacial. Beyond a more or less pronounced terrace step that is partly masked by thick colluvial deposits, successions of sediment units provide interpretable results for most of the Holocene. As a general pattern, prolonged periods of stable conditions, reflected by interposed palaeosols within the profile sections are often faced with relatively short time frames of brief and vigorous sedimentations (Figure 4.10). It is noted that there is a general trend across the Holocene towards a permanent narrowing of the main sedimentation space, accompanied by an increase of the thickness of sedimentary units as well as a shortening of sedimentation periods. From the perspective of a meandering river that creates accommodation space through river bank erosion, the narrowing of sedimentation areas and the increase of sediment thickness may point to decreasing channel activity may be caused by a permanently declining discharge over the Holocene. Or it may either be a matter of a steadily growing landscape fragility that is reflected by a changed sediment load-ratio with a higher sediment supply due to changing climatic conditions or increasing human interventions (chapters 1.1, 2.6 and 3.6).

Another interesting aspect is the strong variety of fluvial architectural patterns along different sections of the lower Guadalete River. Here, step terrace textures, resp. fill-in-fill terrace textures (Schirmer et al. 2005) were observed in the upper downstream section and a transition towards stack terrace textures with the preservation of much older sediments was found in the lower downstream section (chapter 3.4). Such a lack of conformity is perhaps not surprising, especially since the complexity of fluvial systems and in particular the possibility of missing conformity of sedimentation patterns along one and the same river course are already known, e.g. from the studies of
Schumm (1973). However, in this case, results provided important information regarding the conceptional interpretation of the impact of sea-level changes on fluvial dynamics (see chapter 3.5 and 5.2).

However, due to excellent exposure conditions within the study areas it appeared feasible to generate composite profiles with a very well resolved succession of sedimentary layers and floodplain soils (Figures 4.2 and 4.4) that form the basis for ongoing interpretations. After a critical consideration of possible influencing factors in chapter 5.2, an interpretation in terms of palaeo-environmental conditions will be conducted in chapter 5.3.

5.2 Assessment of influencing factors and their relevance for fluvial dynamics

As pointed out in chapter 1.2, the importance of influencing factors on fluvial dynamics is an important issue in the course of that dissertation. Since the degree of climate sensitivity of floodplain dynamics represents one of the major concerns, it is a precondition to first try to identify other influencing factors with the principal intention to separate them from climate. However, even if different influencing factors have been detected, a weighting in terms of the degree of influence will scarcely be successful without working under laboratory conditions as it cannot comply with the complex feedbacks that are inherent to fluvial geomorphologic systems (see e.g. Vandenberghe et al. 2010). Nevertheless, for the purpose of a critical engagement with the derived correlations, a detailed discussion and assessment of potential controlling factors was undertaken in chapters 2.5 and 2.6 for the Jarama River system and in chapter 3.5 for the Guadalete River system. A concluding and comprehensive discussion that is provided in chapter 4.5 with a step by step handling of each factor, yielded the following most significant results.

(1) Intrinsic forcing of fluvial dynamics must generally be taken into account (Schumm 1979). However, intrinsic forcing is difficult to identify and no indications have been found during that study. Thus, further considerations of intrinsic factors will be waived at this point.

(2) Base-level changes were considered less determinant in the Jarama catchment located in central Spain, but they had major influence on fluvial dynamics in the coastal regions, in particular along the Guadalete and Guadalquivir estuaries (Dabrio et al. 2002, Salvany et al. 2011). Here, the fluctuating sea level represents the immediate base level that dropped as much as 120 m during the LGM in the Gulf of Cadiz (see chapter 3.5.1). Accordingly, rivers incised deeply into the coastal plain and the estuaries and dissection of terrace bodies reached far upstream. Beside the LGM, likewise the sea-level drop related to the Younger Dryas was characterized by strong river incision as confirmed by evidences related to the time of abandonment of late Pleistocene terraces in the Guadalete and Guadalquivir river valleys. In general, sea-level drops initiated river incision and sea-level rises introduced fluvial aggradations in the coastal areas, however, especially the evolution of estuaries may be considered as resulting from a
combination between sea-level fluctuations and runoff generating catchment dynamics (‘upstream control’, see e.g. Figure 4.10).

Concerning Holocene dynamics, numerous authors describe the importance of an interrelation between fluvial sediment input and accommodation space controlled by sea-level rise for sedimentation dynamics in coastal areas (see chapter 4.5). Although there were no indications found for marine influence, especially in the Guadalete River valley one has to assume an effect of the marine transgression on sedimentation velocities until the high stand phase starting around 7500 - 6500 cal. BP (e.g. Vis et al. 2008).

(3) Tectonics may play a pivotal role related to amount and rate of incision and sedimentation processes. All study areas are located in tectonically active mountain forelands and are additionally characterized by the appearance of vast deposits of evaporitic marls within the catchments (chapters 2.2.1 and 3.2) that, together, cause a strong tendency to deformation in terms of bulging and subrosion structures (Rodríguez Vidal et al. 1993) as well as the formation of weak zones along fault lines. Apart from a general effect of such deformations on sedimentation and incision rates, a unique example of tectonic impact on fluvial sedimentation dynamics has been documented in the lower Jarama Valley. Here, interplay of tectonic movements and halokinetic deformations caused a juxtaposition of river sections with different inclinations of floodplain gradients, with the consequence that runoff patterns were strongly modified over short distances. This becomes obvious in terms of a large and thick gravel body that was deposited simultaneously and directly adjacent to fine-grained flood loams in mid- to late Holocene times (see chapter 2.5.6 and Figure 4.2). Gravels show a braided river depositional pattern (chapter 2.4.3) and stretch over large areas of the floodplain. On the basis of this architectural element discharge patterns have been identified that have not been expected for this position and this time slot. Figure 5.1 gives an idea about the appearance of the mid-Holocene channel of the Jarama River that branched at a specific position due to sudden changes of the river gradient. Apparently, the tectonic displacements already took place during the last glacial period (chapter 2.4.1). Thus, the transition from erosion towards accumulation around 5 ka cal. BP, and afterwards the change of the discharge pattern from braided style to meandering style may have been triggered by another factor, such as climate. Highly variable discharge peaks are necessary to produce extreme runoff for ample gravel transport and accumulation, which points to highly arid climate conditions during that time. Finally, the dynamics may result from the combination of previous tectonic movements and an accentuated Mediterranean climate during the mid-Holocene (chapter 2.5.6).

(4) The significance of climate for fluvial dynamics is well known as shown in chapter 1.1. The influence of climate conditions on the studied river systems has been assessed using a large number of climatically or, more generally, environmentally relevant secondary archive studies with the aim to compare them to the obtained floodplain records in order to find out dependencies and relationships. Respective correlations are shown in Figures 2.10 and 3.14, and in a more advanced form in Figures 4.8 and 4.9. Obviously, there are strong links between certain environmental developments and the initiation of fluvial dynamic phases, which is discussed in more detail in chapter 5.3. In principle, a significant influence of climate on fluvial dynamics
5 Synthesis

Figure 5.1: Schematic sketch of the lower Jarama Valley between 5 and 4 ka cal. BP. While the channel incises along the rear section that leads to the preservation of early to mid-Holocene flood loams, it branches in the front section and develops a braided river discharge pattern. Thus, early Holocene sediments have been eroded by coarse gravel before the braided channel accumulated a coarse gravel body between 5 and 3 ka cal. BP.

could also be confirmed by these investigations. However, especially in Figure 2.10, where archive information from different parts of Spain has been plotted against each other, it is well visible that there are many mismatches between environmental conditions and fluvial dynamics on the one hand, and between environmental conditions of different regions on the other. This is not the case for Figure 4.9, where just archive studies from the considered region have been used. This shows that climate is certainly suitable to explain floodplain evolution and catchment dynamics, but only in a regional context, which is patently obvious given the strong spatial variability of climatic conditions in Spain reaching from humid in northwestern parts of the Peninsula to highly semi-arid in southeastern parts (see also Hidalgo-Muñoz et al. 2011).

(5) Today, decisive influence on floodplain dynamics is exercised by human activity in the catchment areas (Alonso and Garzón 1997, Gregory 2004, 2006, Wanders and Wada 2014). This influence was almost negligible in the early Holocene, while it increased during the mid- to late Holocene and achieved tremendous dimensions in the last centuries (Faust et al. 2004, Hoffmann et al. 2010, and Suchodoletz et al. in press.). In brief, there was no suitable way to clearly separate human impact from climate influence based on floodplain sediments. However, evidences for human activity have been found in terms of archaeological artifacts within the sediments, and kind and character of floodplain sediments. That means that especially after 2.2 ka cal BP, flood loams bear the characteristics of eroded topsoil horizons originating from catchment slopes that is expressed by blackish colors, humic enrichment, increased clay contents and certain contents of gypsum inherited from surrounding marls (chapter 2.5.8). Beside these indications of human contribution to sediment mobilization and delivery, coincidences between flood loam accumulation and the succession of climate changes (Figures 4.8 and 4.9) suggest a strong coupling between the influence of climate and
humankind on geomorphologic processes. The impact of the factors may in this regard be mutually reinforcing.

5.3 Interpretations in terms of palaeo-environmental conditions

The correlation of floodplain records with regionally relevant environmental archives revealed valuable information regarding the reaction of fluvial systems to environmental changes and it emerged that fluvial dynamics are an expression of landscape evolution within the river catchments. Following main conclusions can be drawn.

(1) Brief and vigorous sedimentation phases generally coincide with times of climate change, implying that landscape and vegetation systems are in a state of utmost fragility during such climatic shifts (chapters 2.5 and 3.5). Knox (1972), Vandenberghe (1995) or Törnqvist (2007) reported about similar relations. Thus, large volumes of sediment have been mobilized and taken to floodplain positions. Short time spans of such sedimentation periods may be due to a fast adaption of preserving vegetation cover to changed environmental conditions.

(2) In periods of prolonged weakening of the environment, such as the aridity period between 5 and 3 ka cal BP in central Spain that was characterized by increased rainfall- and runoff variability, the fluvial system responded with prolonged but somehow diminished floodplain sedimentation.

(3) An environmental change in the course of an incipient aridity phase may take place as follows: the weakening of the vegetation cover and the accentuation of hydrological phenomena cause an increase of surface runoff that in turn promotes slope erosion with the result of sediment mobilization and supply to the drainage system.

(4) Concerning climatic circulation systems that are linked to landscape fragility and fluvial activity (chapter 1.1), the above list shows that flooding periods associated with floodplain aggradations rather relate to arid climate phases, and periods without flooding characterized by floodplain soil formation seem to be related to humid climate phases. That corresponds well to previous studies and concepts by Langbein and Schumm (1958), Knox (1972), Walling and Kleo (1979), Eybergen and Imeson (1989), Lavee et al. (1998), Blum and Törnqvist (2000), Desprat et al. (2003), Faust et al. (2004), Vicente-Serrano et al. (2006), Törnqvist (2007) or Ruiz-Sinoga and Romero Diaz (2010). Corresponding circulation patterns could imply a passing by of moist air masses during arid periods (floodplain activity) and a drift of cyclones straight over Spain during humid periods (floodplain stability). The equivalent considering current circulation patterns would involve negative NAO-index values for the latter case and positive values for aridity periods (see also discussion in chapter 4.5.8).

(6) Concerning human impacts it has been shown that it is difficult to separate these from climatic influence. Since late Holocene flood loams can be considered to be the correlate sediments of human induced soil erosion, it is to be expected that deforestation and cultivation activities may have had an exacerbating effect on environmental pressures that have been exerted during arid phases.
5.4 Comparative consideration of the various study areas

Periods of congruent dynamics in different river catchments are documented in chapter 4.5.4 and were related to the influence of supra regional effective variables. It was found that supra regional floodplain dynamics are strongly linked to hydrological conditions within the catchments, pointing to a close relationship between large-scale climate conditions and major catchment dynamics.

Furthermore, the correlation with data from North Atlantic marine coring (Bard et al. 2000, Pailler and Bard 2002, Berner et al. 2008, Chabaud et al. 2014) highlighted that North Atlantic cooling periods coincide with arid climate conditions and increased landscape dynamics over Iberia, and North Atlantic warm periods can be linked to more humid climate conditions as well as stability and preservation in the river basins. On the other hand, a comparison with data from the Alboran Sea (e.g. Cacho et al. 2001, Fletcher et al. 2010) does not show a high level of correlation at first view that supports the assumption of a complex relationship between marine circulation systems in the Atlantic, climatic circulation systems above the Western Mediterranean, and landscape evolution in terms of geomorphologic system activity in southwestern and central Spain.

The comparison with some of the few available floodplain records from other Western Mediterranean regions (Sancho et al. 2008, Zielhofer et al. 2008) revealed that there is nearly no connection between Atlantic river systems in western and central Spain, and Mediterranean river systems in eastern Spain, but instead stronger parallels between river systems in Atlantic Spain and northern Tunisia (Figure 4.10). This again raises the question whether the influence of an Atlantic climate might be even more relevant for particular regions in the Maghreb than climate-producing mechanisms related to the surrounding Mediterranean Sea.

Apart from above mentioned matching phases, each river system possesses peculiar patterns of fluvial dynamics during certain periods. These may relate to particular regional climates or to a deviating response on certain external or internal factors as intensively discussed in chapter 4.5.5. Examples for the regional importance of tectonics or base-level changes have also been provided in chapter 5.2. A major outcome of this dissertation is, again, the emphasis of regional aspects related to climate patterns, fluvial dynamics, and landscape evolution in general. This circumstance becomes apparent in Figure 2.10, whereby proxy-data from outside the studied regions have been largely excluded in the course of further reflections.

Diverging dynamics within the regions studied in this research may likewise arise from modifications of influencing factors, but to a large extent, it can be related to the basic state of vulnerability of a catchment to external influences. To stay with the factor climate, a certain reduction of the annual amount of rainfall in the course of an aridity period may initiate a strong activation of geomorphologic processes in the one catchment, and barely perceptible reactions in another catchment, dependant on the initial moisture regime that largely determines the buffer capacity of a landscape. The difference of about 200 mm annual precipitation may be responsible for an earlier onset and a longer duration of certain sedimentation periods in the Madrid Basin compared to
5 Synthesis

Lower Andalucía (see Figure 4.10). A higher initial moisture regime with more favorable conditions for vegetation growth may lead to a higher resilience of a landscape to incipient aridification and associated accentuation of rainfall events (principle of the 'Langbein and Schumm' curve, 1958) and thus, a delayed response of geomorphic systems (for more details see chapter 4.5.5). Finally, the interplay between climate system, vegetation system, hydrologic system and geomorphic system becomes decisive for the reaction of fluvial systems, whereas the general physiographic configuration exercises significant influence on these relationships.

5.5 Climate change and implications for fluvial system behavior

The results show that in the Western Mediterranean, climate changes exerted a significant impact on fluvial dynamic patterns in the past. Along a causal chain that ranges from hydrological systems to vegetation cover and runoff patterns, climate changes may initiate strong geomorphic activity of landscape systems, or even phases of landscape stability. Therefore, landscape development is strongly dependant on respective climates, but likewise on the state of fragility. Climate fluctuations have been a natural phenomenon throughout the Holocene. The fragility of landscapes, irrespective of climate forcing, has been unfavorably modified by anthropogenic influence during the Holocene, and especially during the last centuries. This dissertation has shown that landscapes and in particular fluvial systems exhibited serious reactions on past climate fluctuations. Apparently, such reactions had severe consequences on previous civilizations that used floodplains for settlement purposes, which is e.g. reflected by the burial of Roman settlements by fluvial deposits in various studied river catchments (chapter 2.5.8 and Figure 3.3). On the one hand, this evidences the high sensitivity of the Mediterranean realm towards environmental pressure. On the other hand, this documents that floodplains have always been fragile landscape elements that are subject to the permanent risk of degradation due to fluvial erosion and sedimentation processes, depending on the expression of external factors and the resistivity of the catchment.

An important endeavor of reconstructing palaeo-environmental conditions and landscape development is to identify patterns and regularities of fluvial system response to various influences in order to get a key to the prediction of future developments. In view of the current climate change and attendant modifications of hydrological systems in the Mediterranean (see chapter 1.1), it can be assumed that a substantial increase of dynamics will take place in many Iberian watersheds. Examples of recent extreme flood events are manifold, such as the extreme flash-flood in Murcia in September 2012 with ten casualties and material damages of approximately 120 million Euros (Amengual and Homar 2014) or a high flood within the Guadalete Basin in March 2010 that lasted several days and resulted in the deposition of up to 15 cm of clayey sediments in distal floodplain positions. Due to the fact that consequences of climate or environmental changes have apparently been amplified by human land use in the past, it is most likely that landscapes that are recently subject to very intensive utilization may show above-average strength of reaction on hydrological extreme events.
Associated therewith, and as discussed in chapter 4.5.3, the formation of high flood events already starts on slopes of the catchment areas. Thus, an intended mitigation can only be sustainable if attention is given to the entire catchment with the aim of promoting appropriate land use (Sánchez-Canales et al. 2015), to provide better protection against soil erosion and to create a sufficient amount of retention area. Protective measures in flooded areas of river valleys will naturally tread the consequences, not the causes of flooding. It remains to be seen whether the construction of reservoirs, dams and dykes can be suitable means for the disconnection of discharge pathways and inundation areas. For a number of reasons, preventive interventions far away from flooded areas may be difficult to realize, but ultimately, measures to prevent or mitigate flood damages cannot be done without paying attention to the areas where runoff is initially generated.

5.6 Outlook

The majority of the objectives set out in chapter 1.3 were achieved during the studies and a large number of research questions could be answered to a certain degree. However, due to the complexity of processes and interrelations that are linked with fluvial dynamics, it is only comprehensible that a variety of questions remains unanswered. An important issue when dealing with system connectivity and response patterns is the availability of data in form of studied archives. A higher concentration of archive records sensitive to climatic, vegetation, hydrological and geomorphic systems in defined areas would be a great advantage for correlations in terms of dependencies and causal relations. A future aim should therefore be to condense studies on terrestrial archives and to furthermore implement such research in different areas with different physiographic backgrounds in order to examine various external influencing factors.

The effort to closely relate catchment dynamics and floodplain dynamics may strongly benefit from the investigation of subordinated tributary streams that link lowest order catchments and receiving streams. As these intermediary systems constitute important sediment traps, the assessment of chronostratigraphic sequences would provide information of particular importance for questions concerning system connectivity, sediment delivery from sub-catchments, the influence of the main stream on dynamics of its tributaries, or sediment provenances.

The connectivity of discharge pathways, of areas of sediment mobilization and floodplains in particular sections of the valley, even down to the estuary, is still a major research area. By way of example, it appeared that sedimentation dynamics of the lower Jarama River as most important river course in the upper Tajo River catchment, and sedimentation dynamics in the lowermost Tajo Valley (Vis et al. 2008) are difficult to correlate. On the way to the Atlantic, the Tajo River crosses different depositional basins and cuts lifting mountain chains, thus a limited connectivity is thoroughly comprehensible. However, when dealing with extreme flood events and the vulnerability of downstream areas to floods, the degree of connectivity becomes highly relevant, not just in the Tajo system, but likewise along the Duero, Guadiana or Guadalquivir rivers. Beside extensive stratigraphic work, heavy mineral analyses or
comparable approaches of sediment fingerprinting could be an appropriate way to clarify respective issues.

Returning to the floodplain records worked out in this dissertation, they can be of considerable value for the comparison of additional regional studies dealing with fluvial dynamic patterns in the Western Mediterranean, they might help to assess the relevance of geomorphic systems that operate on smaller scales for regional landscape development, and they might be useful for further correlations of large-scale marine and atmospheric circulation patterns with terrestrial system behavior.
5 Synthesis

References


Fletcher, W.J., Sanchez Goñi, M.F., Peyron, O., Dormoy, I., 2010. Abrupt climate changes of the last deglaciation detected in a Western Mediterranean forest record. Climate of the Past 6, 245-264.


Slaymaker, O., 2006. Towards the identification of scaling relations in drainage basin sediment budgets. Geomorphology 80, 8–19.


Übereinstimmungserklärung:

Die Übereinstimmung dieses Exemplars mit dem Original der Dissertation zum Thema:

„Fluvial dynamics in Spain - Significance for palaeoenvironmental reconstructions and landscape evolution in the Western Mediterranean“

wird hiermit bestätigt.

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