‘DESIRE Annual Meeting 2011’

Field guide to the Guadalentín (Spain)

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1 Introduction

Given the severity of the problem in the Guadalentin basin and taking advantage of the long history of research projects, the Guadalentin was selected as the Spanish study area in the DESIRE project. The focus of most research within DESIRE has been on the sub-catchment of the 'Rambla de Torrealvilla', which is considered to be representative for large parts of the Guadalentín basin. See Figures in **Appendix A** for the location and an image of the Guadalentin basin and the Torrealvilla catchment. The Guadalentin basin covers an area of about 3300 km^2. The 'Rambla de Torrealvilla' is a tributary in the headwaters of the Guadalentín upstream of Lorca, and covers about 250 km^2.

During the last two decades, the Guadalentín basin in south-eastern Spain has been the study area for many studies dealing with land degradation. Examples are the projects MEDALUS, DESERTLINKS, MEDACTION, and RECONDES funded by the EU, but also various Spanish national research projects have focused on parts of the Guadalentín basin. One of the reasons for the broad interest in the Guadalentín is that land degradation is generally considered severe in large parts of the basin due to a combination of the Mediterranean climate, characterised by dry summers followed by intense autumn rainfall, an often steep topography with fragile soils on highly erodible lithologies. Moreover, initiated by political and socioeconomic changes, important land use changes have taken place over the last centuries, which have formed an important driver for further land degradation.

This document provides a concise introduction to the Guadalentin basin for the participants of the fifth annual DESIRE meeting from 3-6 October 2011, organised by the Estación Experimental de Zonas Áridas of the Spanish National Research Council (EEZA-CSIC).

2 Biophysical characteristics of the Guadalentín

2.1 Climate, geology and geomorphology

The climate in the Guadalentin varies from semi-arid to sub-humid Mediterranean (see Appendix A), with mean annual precipitation between less than 300 to more than 500 mm, and an average annual temperature between 12 and 18°C. Precipitation shows an inter-annual coefficient of variation between 0.2 and 0.5, though high inter-seasonal variation is also present. Droughts, centred in the summer, commonly last for more than 4-5 months. Annual potential evapotranspiration rates larger than 1000 mm are common in large parts of the basin. With an aridity index (UNESCO, 1979) dominantly between 0.2 and 0.5, the main part of the basin is considered to be semi-arid.

Geologically the Guadalentin basin lies on the eastern edge of the Betic ranges, whose SW-NE axis and faults have determined the main structure of the drainage network. The geomorphology of the area is dominated by strongly folded and faulted (Eocene and Oligocene) limestone hills with footslopes developed in Eocene Marls. The Guadalentin is an ephemeral river for the major part of its course. The upper section of the basin has a rather dense drainage density in the headwater areas of Sierra de Maria (max 2045 m.a.s.l.), Sierra del Gigante (1554 m), Sierra Espuña (1585m), all on Cretaceous and Jurassic limestones and dolomites, and Sierra de las Estancias (1467 m) on Paleozoic shales and phyllites. In the central part of the basin several meseta-like plains at altitudes of ca. 1000 m can be found. The middle section is characterised by an undulating landscape with long pediments and incised river terraces. The lower reach is characterised by a nearly flat valley bottom with series of well developed alluvial fans at the base of the sierras.

2.2 *Soil, vegetation and land use*

The most dominant soil types in the Guadalentin are Regosols, Fluvisols, Calcisols, Gypsisols and Leptosols (FAO, 2006). Leptosols dominate on the steeper slopes of the limestone outcrops, whereas Calcisols, Gypsisols and Regosols are mostly found on the flatter terrain. Calcic and petrocalcic horizons are common in these soils. The main valley of the Guadalentin is dominated by Fluvisols formed in sediments rich in gypsum and calcium carbonate and often with high levels of salinity.

Vegetation in the Guadalentin is highly disturbed by centuries of human influence. Semi-natural ecosystems include shrublands with dominance of *Stipa tenacissima*, *Rosmarinus officinalis* and *Anthyllis cytisoides*. Forests are dominated by *Pinus halepensis*. The main land use in the Guadalentin at present includes under dryland conditions almonds and herbaceous crops, and under irrigation orchards with citrus, various vegetables, greenhouses and also almonds are sometimes irrigated. Figure 4 shows the CORINE 2000 land cover map for the Guadalentin basin. The map shows important areas of irrigated crop concentrated in the main valley of the lower part of the Guadalentin. The headwaters are dominated by dryland farming, open spaces, scrub and forest cover. However, it should be realised that land use is quite dynamic and that important changes have taken place in recent years, and are ongoing, especially in the surface area of irrigated crop.

2.3 *Land use change*

The Guadalentín has seen important structural land use changes over the last centuries. An analysis of land use changes within the Guadalentín between approximately 1900, 1978, and the year 2000 showed that between 1900 and 1978 the main changes consisted of the conversion of dryland herbaceous cropland to shrubs, to dryland almonds, or to irrigated herbaceous crops (Rojo Serrano, 2003). In the same period there was a notable increase in irrigated land, and an increase in plantations of alpha grass (*Stipa tenacissima)* for the production of cellulose. Between 1978 and 2000 the dryland agriculture further decreased, while irrigated land and forest increased.

A detailed study of land use changes since the 1950's within the Torrealvilla catchment performed within DESIRE (Nainggolan et al, in review) shows that more than 72% of the study area has undergone significant land use changes over the past five decades with pronounced effects on landscape composition and structure. This study also showed that afforestation, land abandonment and agricultural intensification are the three main types of land use change occurring in parallel.

2.4 *Groundwater, water transfers, and irrigation*

Due to the profound water deficit in large parts of the Guadalentin basin, irrigation has been applied since long times in order to sustain agricultural production. In Roman and Arabic times sophisticated irrigation schemes and water harvesting techniques were developed and widespread for decades. At the end of the nineteenth century two reservoirs were built (i.e. Valdeinfierno and Puentes) to store water for irrigation purposes. After an initial catastrophic collapse of the Puentes dam in 1802, both dams were rebuilt in 1897 and 1884 respectively. Although these reservoirs allowed the expansion of irrigated agriculture, this was only temporally, as both reservoirs were silted up rapidly. The Valdeinfierno reservoir is nowadays almost completely filled with sediments, and in the Puentes reservoir, that was also filled with sediments, a new and higher dam was finished in the year 2002.

In the search for alternative water resources, the large–scale use of groundwater for irrigation started in 1950's, with the availability of better groundwater pumps and electricity in rural areas (Lopez-Bermudez et al., 2002). Depth to groundwater in these aquifers ranges between 0 and over 200 meters. Over time there has been a strong increase in the water-intensive crops. Therefore, in the upper Guadalentin the number of groundwater pumping stations increased from 25 to 234 between 1973 and 1996, resulting in a lowering of the water table by almost 10 meter per year (Tobarra-Ochoa and Martínez-Gallur, 1998; Romero Diaz et al., 2002). The total annual volume of extracted water increased from 24 hm^3 in 1973 to 56 hm^3 in 1990. In 1996 the extracted volume decreased again to 30 hm^3 due to the lowering of the water table and the high price of water extraction from these greater depths. The irrigated agriculture used close to 83% of total water consumption in the Murcia region in 1999 (Rojo Serrano, 2004). The overexploitation leads not only to a lowering of the water table but also to salt intrusion and a severe salinisation problem.

In order to deal with the overexploited locally available water resources, in 1979 the water transfer from the Tagus to the Segura River was opened. The water transfer was originally authorised to divert up to 600hm^3 from the Tagus to the Segura River annually. Part of this water (25hm^3) was intended for the Guadalentin basin (Tobarra-Ochoa and Martínez-Gallur, 1998). However, the droughts in the 1980's and 1990's made that less than half of the planned volume was actually transferred. Therefore, and in order to cope with the continuously increasing quest for water, various options for water transfers from either the Ebro or the Duero river basin are discussed at national level causing tense public and political debates. Until now regional and national opposition towards more water diversions have prevented the creation of new canals. However, given the fact that irrigated agriculture at this moment is the only profitable form of agriculture without subsidies (Hein, 2007), there is a continuous political pressure to find more water.

3 Socioeconomic characteristics of the Guadalentin basin

3.1 Demography and education

The population density of the Guadalentin basin is highly diverse since there is large variation between rural areas and some medium sized cities within the catchment (e.g. Murcia and Lorca). Population density ranges between 5 and 50 persons per square kilometre for the rural areas and about 472 persons per square kilometre for the municipality of Murcia, the main city in the catchment. For the region of Murcia, there has been a continuous increase in the total population. However, there is a large difference between rural areas and cities within the region. For the rural areas of the region an important decrease in population is observed in the 1930's and between the 1960's- 1970's (CREM, 2008).

3.2 Livelihood, migration, land conversion and land degradation

The main income for people in the rural areas of the Guadalentin basin is from agriculture. Traditionally this involves mainly dryland farming of cereals, almonds and olives in the rural headwaters and irrigated farming of horticulture in flat areas. However, as was indicated before, important land use changes have taken place throughout history in the Guadalentin. In last decades important land abandonment of traditional dryland farming has occurred together with an increase of almond plantations and intensely irrigated horticulture.

Changes in the population are strongly related to changes in land use and to land degradation. On the one hand, high population pressure can cause land degradation, while on the other hand degraded areas with low productivities often show abandonment and low population growth resulting in land use changes. The Guadalentin basin has seen reduced population growth compared to the regional and national average, and the Guadalentin has more people in the age older than 65 years, and less people in the potentially active working population, compared to the regional and national average. Of the working population traditionally a relatively large part has been working in agriculture (close to 50% in the 1980's). However, this percentage has been rapidly decreasing since the 1960's to about 20 % in the 1990's (Romero Diaz et al., 2002).

Parallel to the abandonment of land, developments in the national, European and global economy have been an incentive to shift from dryland agriculture to irrigated crops where possible, and to almond orchards. The Murcia region is now one of the major exporters of lettuce, tomato, melons, peach and other fruits and vegetables. In order to prepare the land for large scale irrigated crop production, land levelling operations are currently taking place at a large scale. Although it is evident that they will have important long-term effects, there is currently no clear view of the extent of these land use changes and on the exact type and quantities of its impact.

In large parts of the Guadalentin reforestation was and is a widely applied conservation measure to combat land degradation. Previously, reforestation was performed on terraces constructed with heavy machinery. Various studies have indicated that in fact these reforestations are very ineffective and even increase runoff erosion rates (e.g. de Wit and Brouwer, 1998). Nowadays it is well accepted that the success of reforestations depends to a large extend on the local climatologic conditions such as effective annual rainfall. There is ongoing research on the effectiveness of reforestations and on the best species and planting techniques to be used in reforestations (e.g. Castillo et al., 2003; Bellot et al., 2004; Barbera et al., 2005; Boix-Fayos et al., 2007).

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5 Excursion stops

EXCURSION STOP 1 (JANTIENE BAARTMAN):

- Controls on late Quaternary landscape development in the upper Guadalentín (See also Appendix E)

- Exploring effects of rainfall intensity and duration on soil erosion at the catchment scale using openLISEM – Prado catchment, SE Spain

EXCURSION STOP 2 (ALBERT SOLÉ & JORIS DE VENTE):

- Field site B: Monitoring of traditional water harvesting (Boquera) and organic mulch to increase the available water for Almonds

EXCURSION STOP 3 (ALBERT SOLÉ & JORIS DE VENTE):

- Field site C: Monitoring of reduced tillage in a cereal field to reduce soil and water loss

EXCURSION STOP 4 (ALBERT SOLÉ & JORIS DE VENTE):

- The Alhagüeces farm and meteorological station

EXCURSION STOP 5 (ALL):

- Lunch at ‘Santa Eulalia Monastery’, Totana

EXCURSION STOP 6 (ALL):

- Visit to the village of Aledo and its tower from which we can see an abandoned urbanization and its geomorphic effects.

EXCURSION STOP 7 (LUUK FLESKENS):

- View of diversity of traditional and more modern land use types of solar panels fields, levelled irrigated horticulture fields and traditional dryland farming.

- Regional effects of local responses to uncertainty of agricultural water supply in Murcia, Spain

Appendix A: Figures

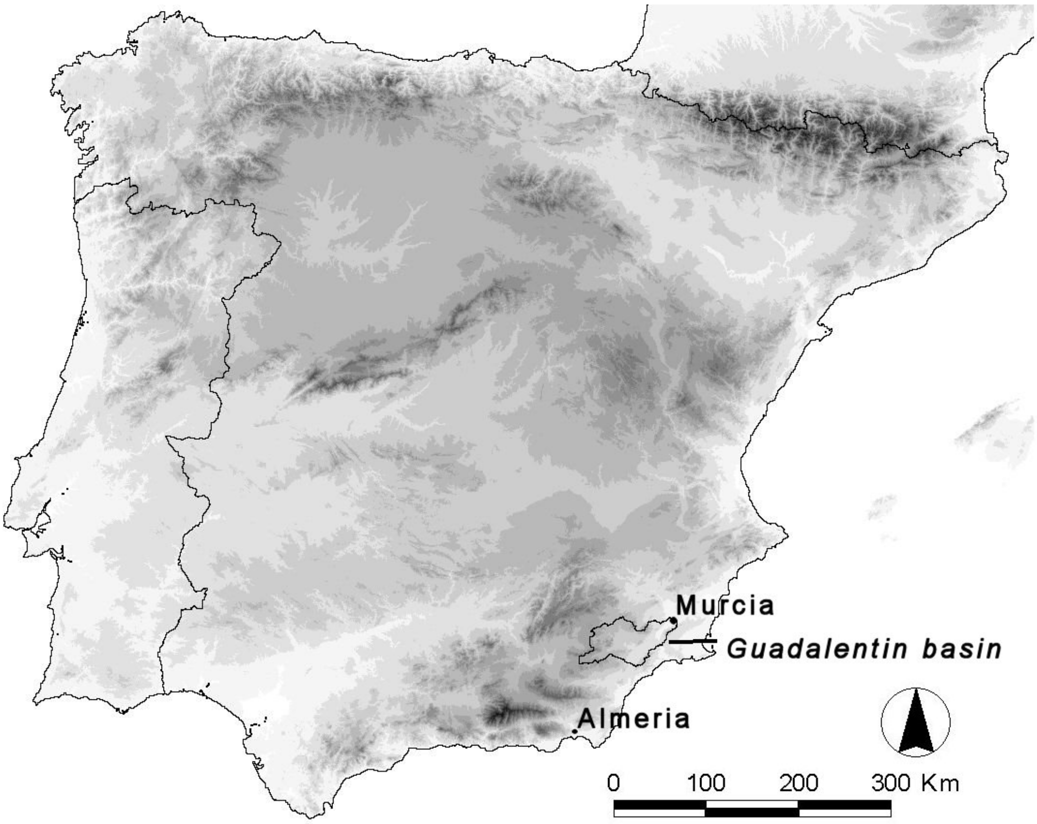
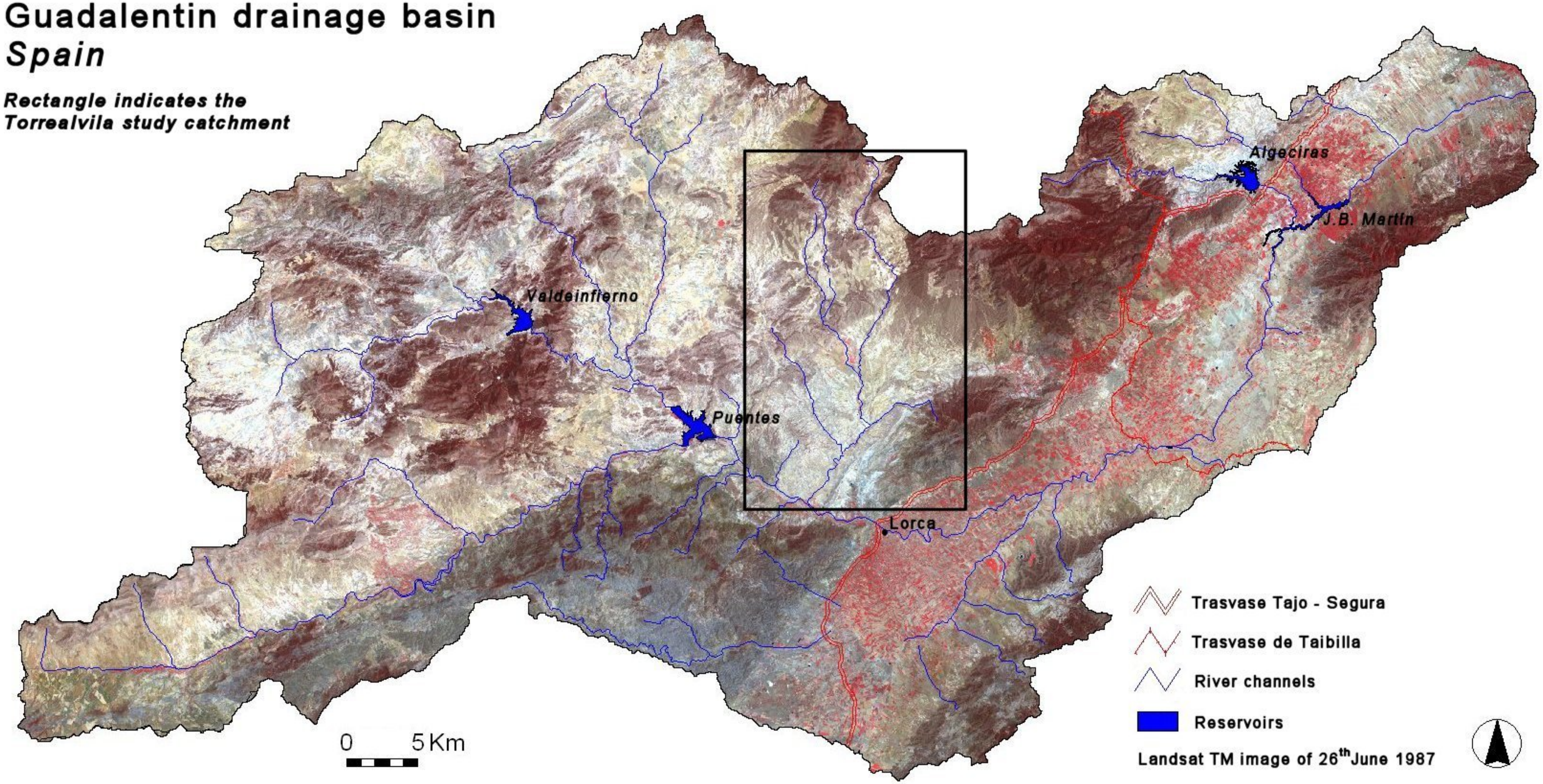


Figure 1: Location of the Guadalentín drainage basin in Spain.

Guadalentin drainage basin
Spain

Rectangle indicates the Torrealvila study catchment



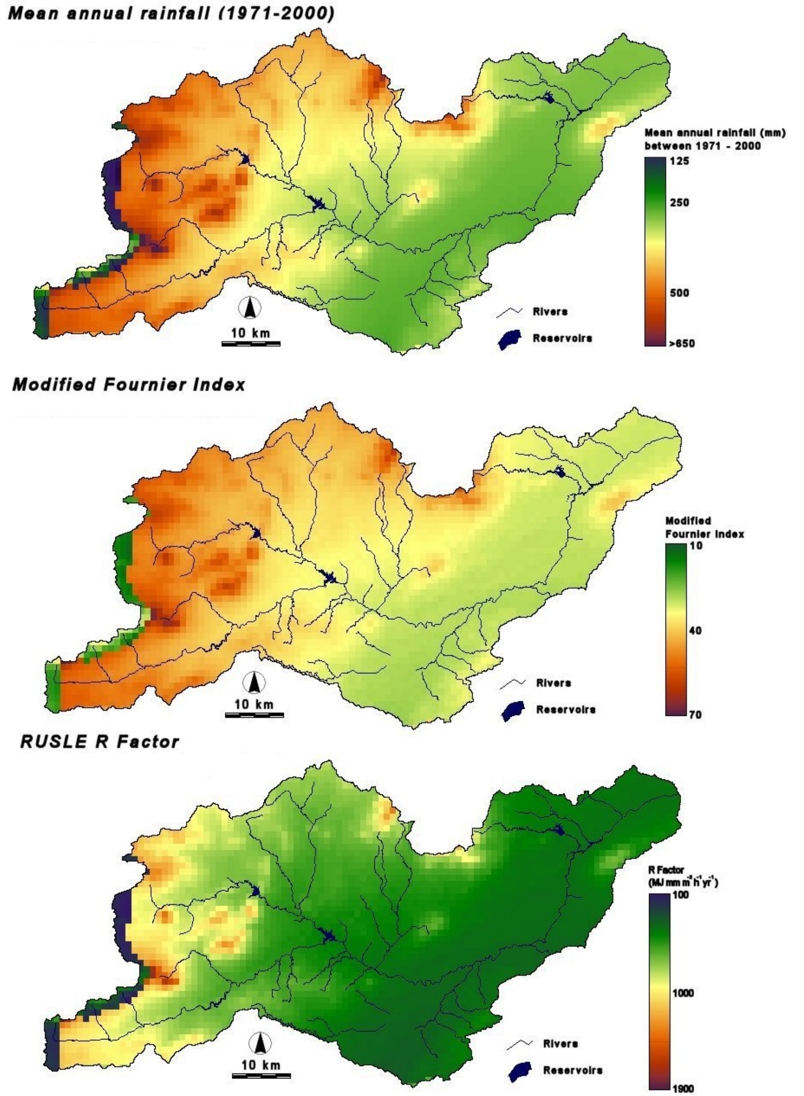


Fig. 3: Rainfall characteristics in the Guadalentin based on annual rainfall in the period 1971-2000.

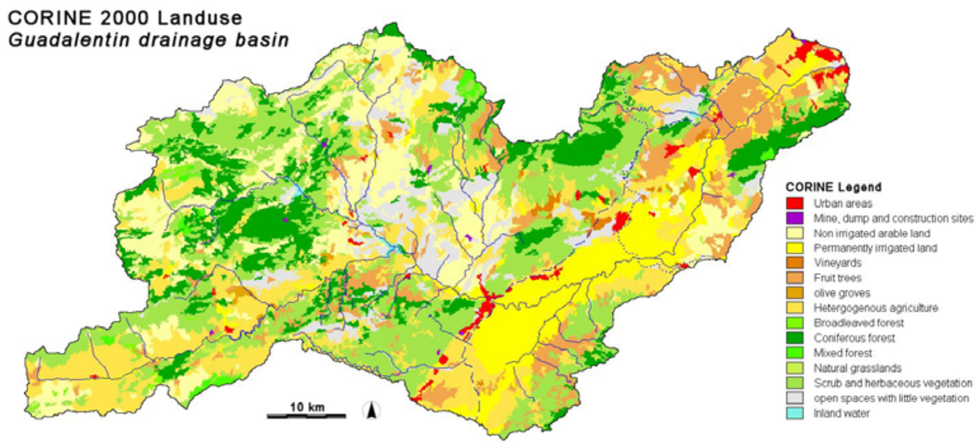
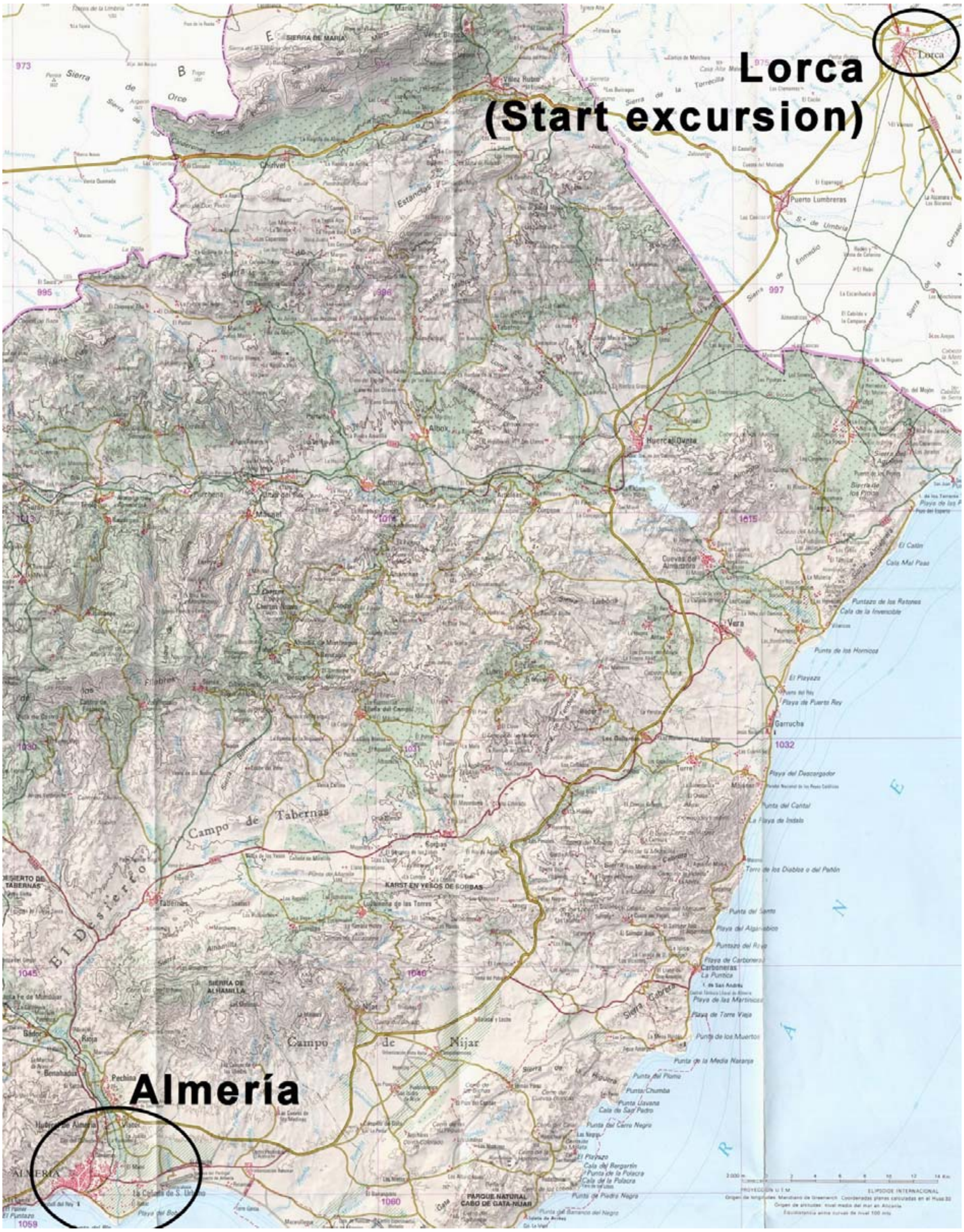
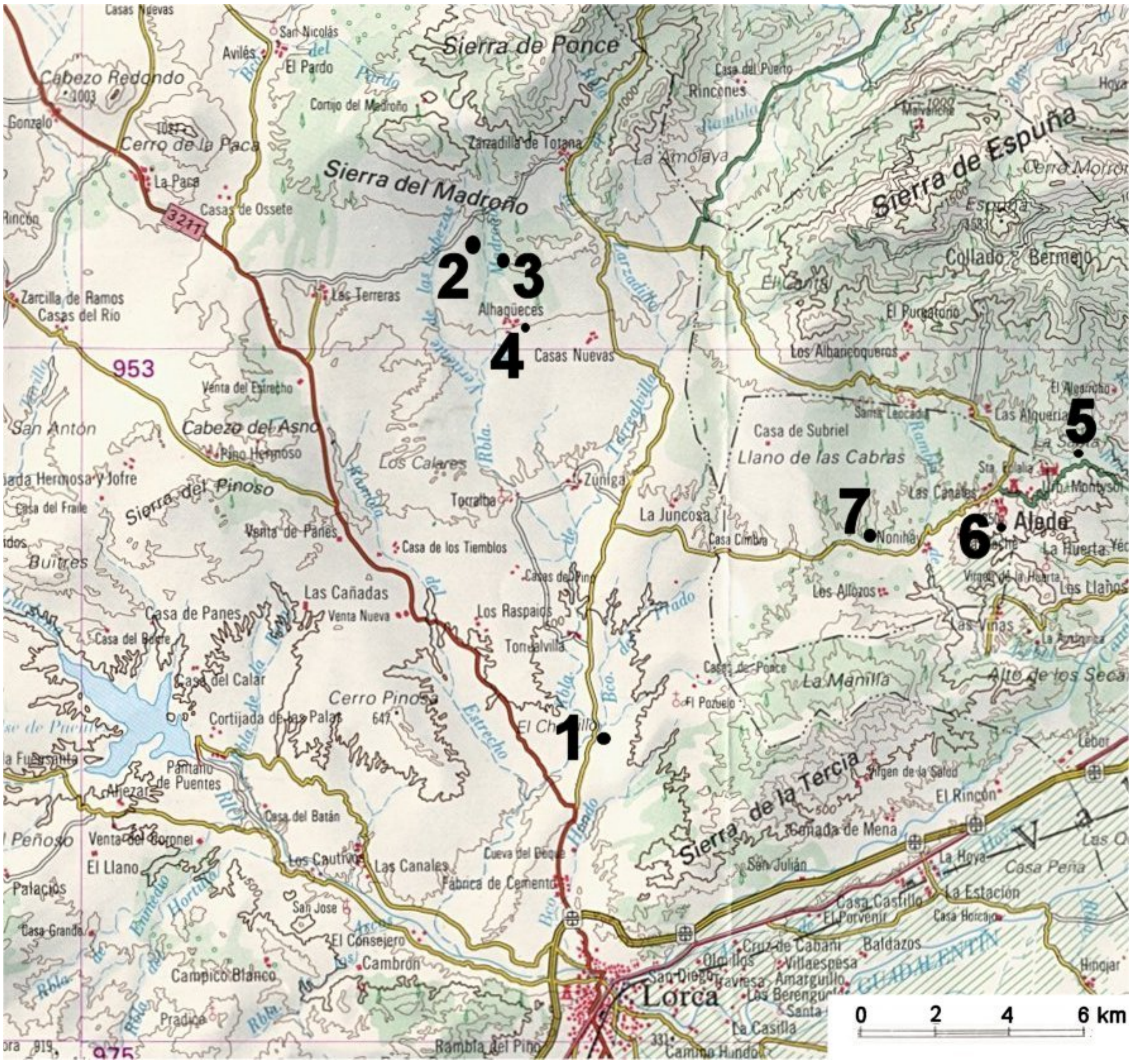


Figure 4: CORINE 2000 land use map of the Guadalentin basin. This map was extracted from the CORINE map of Spain, published by EEA.

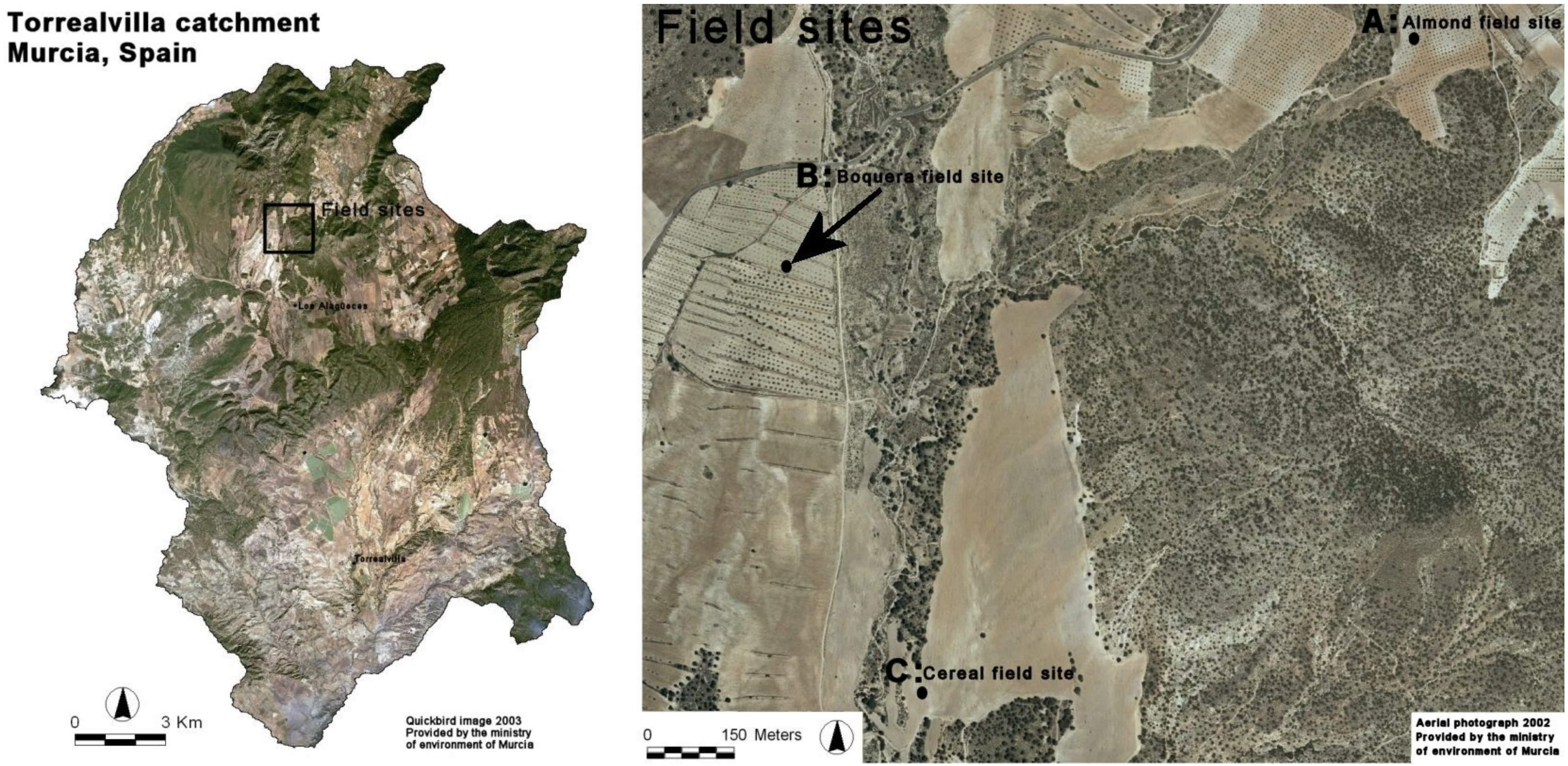
Appendix B: Excursion route maps



B1: Route from Almeria to the Guadalentín catchment (Lorca)



B1: Route and excursion stops in the Torrealvilla catchment



B3: Detailed view of the DESIRE study sites(A, B, C)

Appendix C:

Regional effects of local responses to uncertainty of agricultural water supply in Murcia, Spain[1]

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Abstract

Agricultural development in the Murcia autonomous region has taken place at huge environmental costs, especially overexploitation of groundwater resources. Policy options to tackle this unsustainable situation include inter-basin water transfer (IBWT) schemes from wetter regions in the north and water taxation to further control groundwater abstraction. Farmers could face higher water costs (for those with current access to water) or first time availability of water resources through IBWT (for those in areas where water was previously not available). Through discrete choice based interviews with farmers in the Torrealvilla catchment, in which they indicate how they would adapt their land use in each case, we evaluate how these policy options may influence land use. Aggregating the results to five agricultural enterprises (irrigated vegetables and fruits, grapes, olives and almonds, grains and livestock) allowed land use changes to be scaled up to the Murcia region. At this aggregated level, using input-output analysis, we evaluate the effects of the water scenarios on: i) the regional economy; and ii) the regional water budget. We conclude that appropriate taxation leads to better water use efficiency, but that this is delicate as relatively small changes in prices of agricultural products may have very significant effects on land use and water consumption. New IBWT would considerably increase regional water consumption and the regional economy's dependence on water, and may not be sustainable in the longer term under future climate change.

1. Introduction

The Region of Murcia, despite being hot and dry, has witnessed remarkable agricultural development over the last decades. However, its agricultural sector is premised on heavy overexploitation of groundwater resources and reliance on the Tagus–Segura inter-basin water transfer (IBWT) scheme, which was inaugurated in 1979 (Garrido et al., 2006; Grindlay et al., 2011). The region has become known as a major producer of fruits and vegetables. This is reflected in the importance of agriculture in the economy (8.3% of regional employment and 5.8% of regional gross added value against 4.5% and 2.6% at the national level, respectively), but most significantly by the fact that agricultural exports make up 35.4% of Murcia's total exports (CREM, 2010). For the past thirty years, regional water demand in the Segura basin has surpassed availability as a combined effect of increased irrigation and rapid urbanization (Grindlay et al., 2011). As a result, ironically, the IBWT scheme has only further aggravated the region's chronic water shortage. The water thirst of the region is stressed by many authors, with Garrido et al. (2006, p.347) classifying the Segura basin as 'one of the most interesting cases of water conflicts in Spain, and perhaps worldwide'. Ambitious but highly contested plans for a further Ebro–Segura IBWT scheme have for the time being been put on hold. Simultaneously, the European Water Framework Directive (WFD) prescribes that water should be priced at full-cost recovery and water resources and fluxes should be systematically monitored. The WFD further stresses institutionalising environmental water demands at par with societal and economic water demands. As a consequence, the Tagus–Segura IBWT may be limited by allocating more water within the conceding basin (Martínez-Santos et al., 2008), and prices of groundwater extraction would also rise (Garrido et al., 2006). In this context,

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[1] This is a synopsis of an equally-titled paper forthcoming in Regional Environmental Change

water users generally have great uncertainty over water availability and regulations governing its use.

2. Methodology

As the agricultural sector is embedded in the regional economy, shifts in competitiveness of land uses can have important knock-on effects on other sectors. We combine discrete choice based interviews (DCI) with an input-output model to assess not only the direct aggregate effects of individual land use decisions, but also of indirect effects on the regional economy and associated water use. Setting up the I/O model requires several intermediate steps (only very briefly explained here). The DCI were obtained from a farm survey among farmers in the Torrealvilla catchment. The effects of the DCI-elicited land use change scenarios can be assessed with the I/O model. We also triangulate the DCI responses by using virtual water multipliers in the I/O framework.

2.1. Input-Output model

I/O analysis, initially developed by Wassily Leontief (1936) and still widely used today, is a method to analyse interrelations between sectors of an economy. To perform I/O analysis, one needs to construct an I/O matrix (usually provided by national statistical offices) which represents the intersectoral flows of products (usually in monetary terms and for a specific time period – i.e. a year) from each of the sectors (producer) to each of the sectors (purchaser) (Miller and Blair, 2009). These intersectoral flows are relatively stable: e.g. to produce a unit worth of margarine a more or less fixed quantity of oilseeds is needed. The stability of unitary intersectoral flows, which have become known as inter-industry technical coefficients, is a fundamental assumption of the I/O model. Once an I/O matrix is constructed, I/O modelling entails the analysis of changes in final demand, inter-industry coefficients or value added through a system of linear equations. A symmetrical set of I/O tables containing 73 x 73 sectors is available for Spain for 2005, produced by the National Statistics Institute (INE, 2009). I/O tables have been constructed for many Spanish autonomous regions, but not for Murcia. Therefore we needed to construct a regional I/O table based on the national one. A well-known problem in constructing regional I/O tables is that inter-industry technical coefficients are prone to be exaggerated as the propensity of sectors to import is inversely related to the size of the economy considered (Boomsma and Oosterhaven, 1992; Harris and Liu, 1998; Flegg and Tohmo, in press). We applied the method described by Flegg and Tohmo (in press), building on earlier work by the same author(s), which takes this issue into account. We subsequently tested the method by comparing the output multipliers from non-survey I/O tables based on various location quotient approaches with those from survey-based I/O tables which are available for the neighbouring autonomous regions Valencia and Andalucía.

2.2. Disaggregating the agricultural sector of the regional I/O table

We are interested in the effects of agricultural land use changes and therefore need to subdivide the single agricultural sector into a series of agricultural subsectors. These are defined based on importance of land use, extent of recent changes and differences in water use and economic dissimilarity: 1) grains and other annual field crops; 2) horticulture and fruit trees; 3) grapes; 4) olives and almonds; and 5) livestock. Various regional agricultural statistics were used to achieve this.

2.3. Estimating regional final demand and sector output

Most required final demand data for Murcia were obtained from CREM (2010). National sector final demand scaled down using employment data was used to fill regional data gaps. Good regional data on exports were available. As expected, the regional and national level data bear little relation, both in overall size (regional exports were 20 times larger than the scaled national data) and structure (r^2=0.07). After deciding on the location quotient method to employ, the regional total final demand vector was substituted in the IO accounting equation to estimate total regional output. Agricultural sector output data was available from CREM (2010) and was used in further analyses together with simulated output for industrial and service sectors.

Table 1. Direct water consumption of selected sectors.

Sectors	Water consumption calculated with available data			Harmonized water consumption data	
	Murcia*	Andalucía*	Spain*	Murcia	
	DWC (litre €$^{-1}$)			DWC (litre €$^{-1}$)	DWC (10^3 m^3)
Agriculture	274	-	395	274	563,096
Grains	190	1833	-	190	6,979
Horticulture and fruits	345	683	-	345	468,832
Grapes	505	695	-	505	52,440
Olives and almonds	179	655	-	179	17,836
Livestock	37	15	-	37	17,009
Fisheries	0	0	0	0	0
Industry	2.4	-	0.7	2.1	21,770
Agro-food industries	3.5	3.3	0.9	3.3	9,242
Paper, printing and publishing	0.3	38.3	0.4	0.2	90
Chemical industry	8.1	25.0	1.3	4.5	6,374
Rubber and plastics	3.6	2.0	2.1	4.7	1,038
Metallurgy	2.4	3.6	0.5	2.6	1,692
Construction	-	2.4	0.2	0.2	208
Services	1.5	-	0.7	1.5	31,209
Hotels and restaurants	10.4	18.3	-	3.8	8,358
Education	-	5.0	-	2.0	2,018
Health and social services	-	5.0	-	2.0	3,173
Public administration	2.0	4.7	-	2.0	3,288
Other community and personal services	-	13.3	-	2.8	4,188

* Sources: Murcia – authors' calculations based on available statistics (CARM, 2010); years of estimates vary: 2005 for agriculture, 1999 for industry, and 2007 for services. Andalucía – based on Consejería de Medio Ambiente (1996), using a conversion rate of 1 EUR = 166 ESP. Spain – based on INE (2010).

2.4. Creating water I/O table

Regional water statistics (CREM, 2010) were available as a basis to calculate sectoral water use for agriculture (data relating to year 2005) and industry (year 1999), but not for services. Data for 2007 from the piped water distribution network used in economic sectors and the available statistics were used together with equivalent data from Andalucía (Consejería de Medio Ambiente, 1996) and Spain (INE, 2010) to calculate Direct Water Consumption (DWC) and to harmonise sectoral water consumption (Table 1). Agricultural water productivity in Murcia is high in comparison with Andalucía and Spain. In the case of Murcia, grains and olives and almonds are hardly irrigated. The bulk of water is used in producing high value fruit and vegetable crops. The high DWC in Andalucía may stem from significant water use in low value crops (grains) and relatively wasteful irrigation techniques: 45% of irrigation is by gravity (Dietzenbacher and Velázquez, 2007). In contrast, in Murcia 85% of water is supplied to crops by drip irrigation (CREM, 2010). Backward linkages water multipliers represent how much water is used indirectly in a given sector by considering the water consumption for its intermediate consumption in relation to direct water use. Forward linkages water multipliers represent the ratio of additional water use in purchasing sectors relative to the direct water consumption 'embedded' in output from the supplying sector considered.

Table 2. Current and future land use (area percentage) in Torrealvilla and Murcia under different scenarios.

	Current	Percentage of total land					Percentage of current land use (=100)				
		A	B	C	D1	D2	A	B	C	D1	D2
Torrealvilla:											
Livestock	1.0	0.0	0.2	0.7	2.0	2.8	0.0	19.7	68.9	196.7	275.4
Vegetables & fruits	10.3	0.0	0.2	4.2	17.1	23.1	0.0	1.9	40.3	164.0	221.5
Grapes	2.7	0.1	0.3	1.1	13.4	13.4	3.6	10.9	40.1	488.0	488.0
Olives & almonds	27.2	12.1	9.9	17.6	15.3	15.3	44.5	36.4	64.7	56.2	56.2
Grains	35.2	36.0	35.6	36.2	31.8	24.9	102.3	101.2	102.9	90.4	70.8
Non-used UAA	23.4	51.8	53.8	40.2	20.5	20.5	221.2	229.8	171.7	87.6	87.6
Murcia:											
Livestock	1.7	0.0	0.3	1.1	2.3	2.5	0.0	17.8	65.1	136.2	148.0
Vegetables & fruits	18.9	0.0	0.4	7.6	23.1	24.9	0.0	2.1	40.2	122.2	131.8
Grapes	5.8	0.2	0.7	2.3	10.9	10.9	3.5	12.1	39.9	188.9	188.9
Olives & almonds	17.5	8.2	6.6	11.6	11.4	11.4	46.7	37.6	66.1	65.0	65.0
Grains	10.2	11.7	11.0	12.0	12.0	10.0	114.3	107.5	117.2	117.2	97.7
Non-used UAA	45.9	79.9	81.1	65.3	40.2	40.2	174.2	176.8	142.4	87.7	87.7

Source: current land use determined from satellite imagery (Torrealvilla) and regional statistics (Murcia); scenario results calculated from discrete choice interviews. See main text for description of scenarios.

2.5. Water scarcity scenarios and farmers' land use responses in Torrealvilla catchment

Interviews were administered with farmers within the Torrealvilla catchment (266 km^2 of which 140 km^2 qualifies as Usable Agricultural Area (UAA) of the Guadalentin Basin in Murcia. In total 99 valid interviews were carried out. Sampling was done using the snowball method, making sure all land uses (see Table 2) were covered. The final number of respondents was 7 for grains, 24 for almonds and olives, 32 for grapes, 24 for horticulture and fruits and 12 for livestock. In part, the interviews were intended to capture farmers' responses to hypothetical scenarios that reflect future uncertainty of water availability. The scenarios were developed based on insights gained through discussions with farmers in the area during preliminary site visits. Different scenarios were presented to farmers who currently have access to water and those who do not. The former group of farmers was asked how the following will affect the future of their current principal land use:

- Scenario A – No access to water for agricultural use (total water depletion or deterioration);
- Scenario B – Government imposes tax on groundwater abstraction resulting in a water price higher than maximum willingness to pay for water[2]; and
- Scenario C – Government imposes tax on groundwater abstraction resulting in a water price of up to the individual farmer's maximum WTP.

Farmers' responses were: 1) no change; 2) conversion to other agricultural land uses; and 3) stop farming/abandonment.

In contrast, farmers who currently do not have access to water were asked how their principal agricultural land use may alter if water became available, e.g. through IBWT. This led to a fourth scenario (D):

- Scenario D1 – Water becomes available to previously non-irrigable areas.
- Scenario D2 – as Scenario D1, but for the grain farmers we adopted weights of conversion to irrigated farming as elicited from olive and almond farmers (i.e. increasing propensity of grain farmers to change).

The responses registered in Scenarios D1 and D2 were: 1) no change; 2) increase production (expansion); and 3) conversion to irrigated agriculture. For the purposes of expansion we assumed only the 140 km^2 of UAA in Torrealvilla catchment to be available.

2.6. Upscaling local scenario responses to the Murcia region

[2] WTP individual farmers: lowest €0.20 m^{-3}; highest €0.60 m^{-3}; average €0.31 m^{-3}; standard deviation €0.08 m^{-3}

As all interviews were conducted within the Torrealvilla catchment area, we must take into account the relative shares of each land use when upscaling to the Region of Murcia. We thereby assume that there are no differences in the agricultural production structure of subsectors between the local and regional area. Regional effects of the DCI-elicited responses to water uncertainty scenarios can now be assessed with the I/O tables. Total regional effects are defined as the sum of direct effects and the combined backward and forward indirect effects (Grêt-Regamey and Kytzia, 2007). An analogous procedure is followed to assess the direct and indirect effects of the changed total sector water demands.

2.7. Effect of increased water cost on sector unitary output prices

With the preceding steps, we can now simulate the impact of increased water costs on sector unitary output prices. We will assume that increased costs for water only apply to agricultural water use, assuming that other sectors already pay more for water (e.g. twice as much in neighbouring Almería province – Downward and Taylor, 2008). A so-called virtual water multiplier (VWM) can be used to calculate product price increase as a result of water price increase (the VWM itself representing a price increase of €1). We will present the effects of a price increase of €0.10 m^{-3} – equal to the average incremental WTP (€0.04 m^{-3}) plus one standard deviation (€0.06 m^{-3}) to account for possible understatement (the range of incremental WTP was €0.00–0.25 m^{-3}). The cumulative effects of the water price increase, through water input-output relations, on product prices can help to understand farmer responses to the discrete choice scenarios.

3. Results

3.1. Regional I/O Table for Murcia with disaggregated agricultural sector

The regional I/O table constructed for Murcia was evaluated by applying the same method to neighbouring autonomous regions for which survey-based I/O tables were available: Andalucía and Valencia. This informed the selection of an appropriate LQ to develop a non-survey based regional input-output table for Murcia. Table 4 shows details about the disaggregation of agriculture in five subsectors at the regional scale. All subsectors except livestock occupy sizeable shares of the region's agricultural area (11-36%). However, in terms of output value, grains (2%), grapes (5%) and olives and almonds (5%) contribute only modestly compared with livestock (22%) and especially vegetables and fruits (66%). As a result, productivity per area unit ranges widely. Production structures of the subsectors are therefore also expected to vary considerably. The backward output multipliers of individual subsectors of the disaggregated I/O table varied between 1.22 for vegetables and fruits and 1.86 for livestock (Table 5). The first reflects that relatively little economic activity is generated by producing an Euro worth of horticultural produce, whereas the opposite holds for livestock. Individual agricultural sectors have forward multipliers of 2.11-2.28, which demonstrates that much of their produce is sold to upstream industries. The vegetables and fruits subsector (1.31) is an exception, as produce is not processed in agro-industries but marketed to consumers and – importantly – exported. For all agricultural subsectors, forward linkages are higher than backward linkages. Agro-food industries and construction are sectors with high backward linkages, whereas construction materials and lumber industries have high forward linkages.

3.2. Regional I/O Table of water use

Agriculture consumes about 80% of total ('blue') water use in Murcia: households consume about 15%; and other economic sectors together account for only 5%. Not surprisingly, technical coefficients of water use are a fraction of the technical coefficients based on the monetary value of intermediate consumption. The water multipliers (both backward and forward) of the agricultural subsectors are thus low in comparison to output multipliers (Table 5). Livestock is the subsector with the highest backward water multiplier (1.65): its intermediate consumption relies on water-intensive inputs. Grains have the highest forward multiplier (1.28): the sectors grains are supplied to use a considerable amount of water, whereas water needs for grains are relatively low. Similarly, vegetables and fruits have the lowest non-zero forward water multiplier (1.03). Very little additional water is used to produce output in processing sectors (which moreover absorb only a limited part of total vegetables and fruits output). The modest water multipliers for agricultural subsectors contrast with some of the water multipliers in industries and services. Backward multipliers are very high for lumber and cork industries (33.71), agro-food industries (13.60), and paper, printing and publishing (10.74). These sectors thus require water-intensive inputs totalling several times their direct water demand. Machineries and mechanical equipment (23.06) and financial brokerage (18.46) have very high forward water multipliers: their output is produced with relatively low amounts of water, but the output of purchasing sectors requires a multiple factor total water input.

Table 4. Summary data of agricultural subsectors.

	Output (M€)	Area (10^3 ha)	Productivity (€ ha^{-1})	Water use (Mm^3)	(m^3 ha^{-1})	(m^3 €$^{-1}$)
Livestock	455.5	10.0[a]	45550[a]	17.0	1701	0.04
Vegetables & fruits	1357.1	111.9	12129	468.8	4190	0.35
Grapes	103.9	34.2	3041	52.4	1535	0.50
Olives & almonds	99.7	103.9	960	17.8	172	0.18
Grains	36.7	60.6	606	7.0	115	0.19
Total	2052.9	311.1		563.1		

Source: based on various regional statistics (CREM, 2010) and secondary data. [a] Livestock farming is intensive (i.e. not land-based, two-thirds of output value is pork) and does not appear in regional land use statistics. A nominal area of 10,000 ha has been assumed for this subsector.

Table 5. Output and water multipliers for selected sectors in the regional economy of Murcia.

Sectors	Output multipliers		Water multipliers	
	Forward	Backward	Forward	Backward
Agriculture (current land use configuration)	1.60	1.38	1.09	1.06
Grains	2.28	1.48	1.28	1.17
Horticulture and fruits	1.31	1.22	1.03	1.02
Grapes	2.18	1.36	1.07	1.10
Olives and almonds	2.27	1.41	1.14	1.11
Livestock	2.11	1.86	1.23	1.65
Fisheries	1.15	1.27	1.00	1.00
Industry				
Agro-food industries	1.31	1.80	1.81	13.60
Lumber and cork industries	1.96	1.60	10.40	33.71
Paper, printing and publishing	1.76	1.41	11.50	10.74
Chemical industry	1.50	1.41	2.71	1.26
Machineries and mechanical equipment	1.45	1.34	23.06	4.89
Construction	1.44	1.77	3.13	4.60
Services				
Trade (incl. servicing of vehicles)	1.31	1.41	11.49	3.59
Hotels and restaurants	1.08	1.25	1.05	1.74
Financial brokerage	1.58	1.28	18.46	2.31
Education	1.04	1.12	1.12	1.18
Health and social services	1.07	1.29	1.14	1.36

Source: input-output model results; see main text for procedures and assumptions made.

3.3. Discrete choices and land use change scenarios in Torrealvilla

When farmers with current access to water were asked what their strategy would be if water resources would be completely depleted, the vast majority would give up farming (Figure 1, Scenario A). A sizeable minority (43%) of olive and almond farmers would not change land use, a strategy also followed by 3% of vineyard managers. Remaining farmers would resort to rainfed cropping. A similar pattern emerged when the same group of farmers was confronted with high (perceived) water taxation (Scenario B); again the most common response was abandonment. Continuation of the current land use was the preferred strategy of 36% of olive and almond farmers, 17% of livestock farmers, 12% of vineyard managers and only 2% of horticulturalists and fruit growers. Some vineyards and fruit orchards would convert to olive and almond groves and grains, respectively. Under low (perceived) water taxation (Scenario C) the majority (67% and 64%) of livestock and olive and almond farmers would continue current land use. However, 54% of vineyard managers and 52% of horticulturalists and fruit growers would abandon their enterprises whereas 40% would continue. Some 17% of livestock farmers and 8% of horticulturalists and fruit growers would opt for a change to grains, and 5% of vineyard managers would switch to olives and almonds. These three discrete choice scenarios show that water availability and affordability is a crucial factor for all with current access to water, particularly for horticulture and fruit growing, vineyards and livestock farming. Figure 1 also shows scenarios presented to farmers who currently do not have access to water. If a new IBWT project would be realized, some unused land would start to be cultivated to grains (8%) and olives and almonds (5%). Olive and almond groves would see considerable conversion to horticulture and fruit growing (24%) and vineyards (21%). Moreover, 14% of grain fields would be developed to vineyards. Overall, olive and almond farmers demonstrated the most dynamic choices. If the changes above were to occur, land use in the Torrealvilla catchment would change as shown in Table 2.

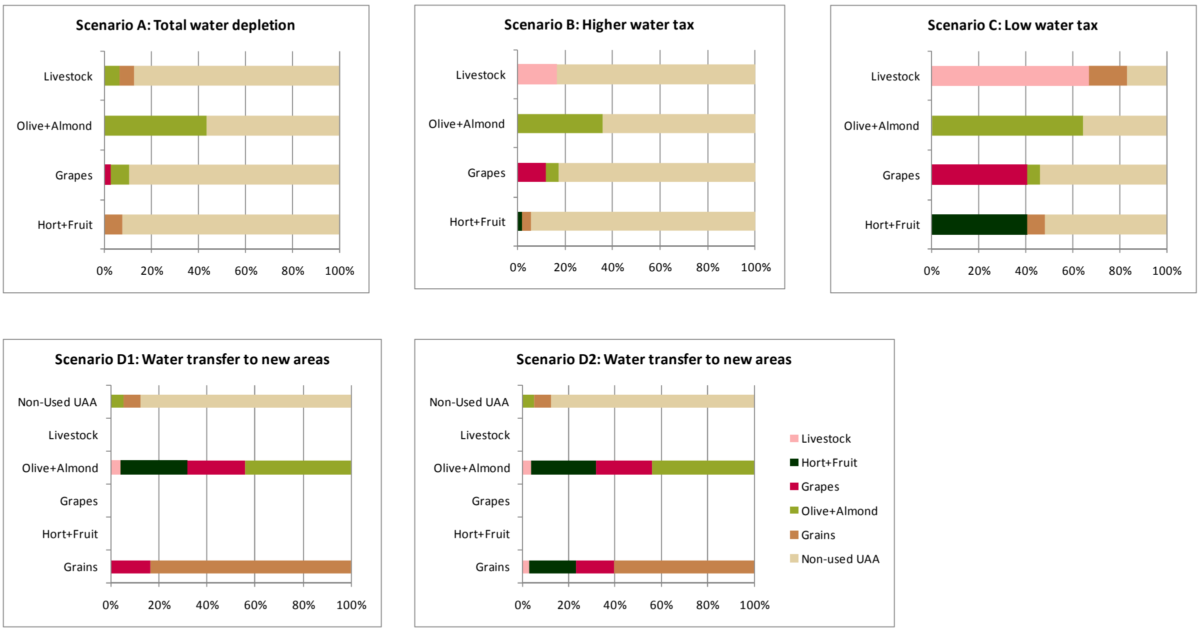

Figure 1. Land use changes under different scenarios in Torrealvilla catchment as recorded from discrete-choice interviews.

3.4. Regional effects of land use change scenarios

When we simulate the effects of the discrete choice scenarios in the input-output model, the land use change scenarios driven by uncertainty in water supply result in diverging effects on regional economy and water demand (Figure 2). The total water depletion scenario almost eradicates the agricultural sector, and when taking into account forward and backward linkages leads to a shrinking of the regional economy of 14%. As all irrigated agriculture disappears in this scenario, this scenario reduces the demand for water to about 18% of the current level. A high water tax has just slightly lower impact. A low water tax impacts the regional economic output by 7% while reducing water demand to almost half the current level. A new water transfer may lead to 4-5% economic growth while requiring 23-30% more water compared to current regional demand. The ratio of economic impact to water demand reveals interesting results. When left to abandonment because of a total depletion of water, with the loss of each cubic metre of water output decreases by €5.57. When introducing a high water tax this ratio is reduced to €5.36 per m^3, whereas a low water tax results in a loss of €4.85 per m^3. Increased water availability similarly augments regional economic output by €5.63-5.86 per m^3.

3.5. Water price effects

Table 6 shows the effects of 'acceptable' agricultural water price increase on the product price of each sector. Although the horticulture and fruits subsector uses more water, it produces more output per unit of water and hence the effects of water price increases are not as pronounced as for grapes and olives and almonds. The 'acceptable' water price increase represents almost 50% of the currently paid average price and leads to agricultural product price increases between 0.6 and 5.6%, with three out of five subsectors being affected by over 3%. Agro-food (0.4%) and lumber and cork (0.1%) industries are the two non-agriculture sectors where a price effect is notable.

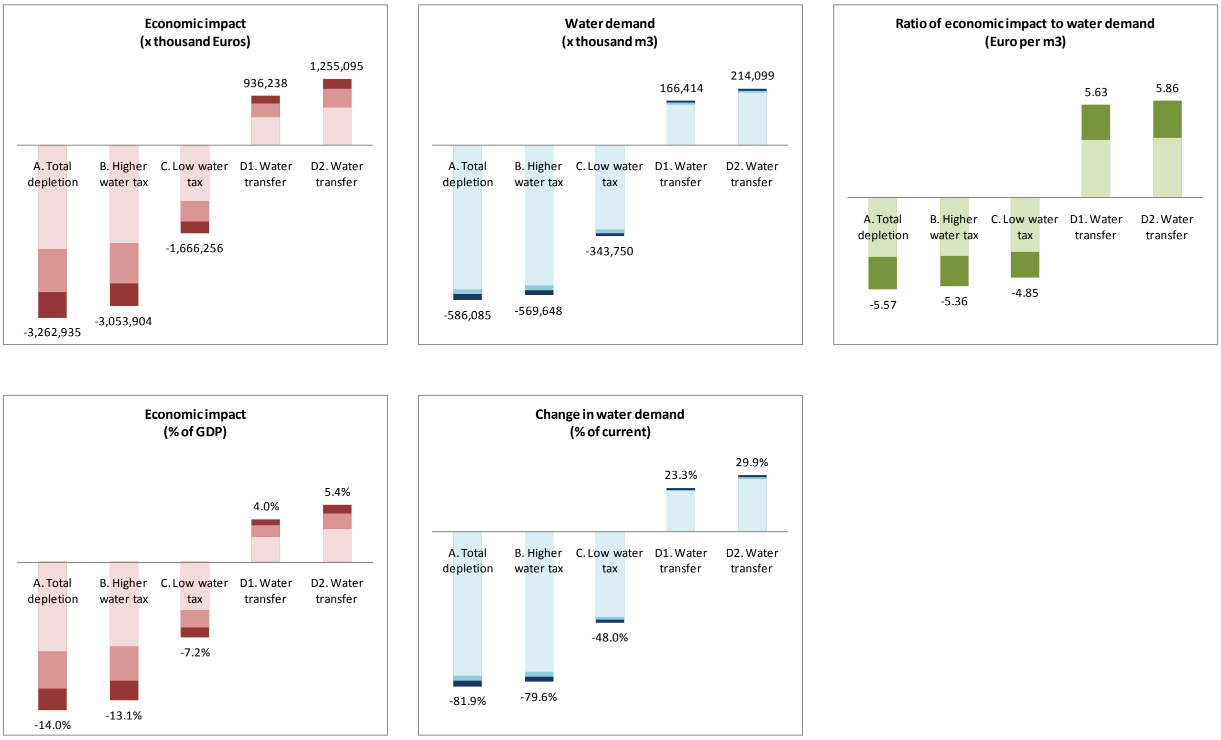

Figure 2. Direct and indirect effects of scenarios on the regional economy and water demand.

Table 6. Impact on output price of selected sectors as a result of price increases for agricultural water use.

Sectors	Virtual Water Multiplier (litre €$^{-1}$)	Impact on product price of a water price increase of €0.10 m^{-3} (%)
Agriculture		
Grains	221.96	2.22
Horticulture and fruits	353.95	3.54
Grapes	558.36	5.58
Olives and almonds	379.69	3.80
Livestock	62.12	0.62
Fisheries	0.43	0.00
Industry		
Agro-food industries	43.50	0.44
Lumber and cork industries	11.81	0.12
Paper, printing and publishing	1.84	0.02
Chemical industry	0.30	0.00
Rubber and plastics	0.97	0.01
Construction	0.20	0.00
Services		
Trade (incl. servicing of vehicles)	0.60	0.01
Hotels and restaurants	2.69	0.03
Health and social services	0.25	0.00
Public administration	0.38	0.00
Other community and personal services	1.01	0.01

Source: input-output model results; see main text for procedures and assumptions made.

4. Discussion

- The I/O table for Murcia needed to be constructed first to enable subsequent scenario analyses. Without survey-based I/O tables for neighbouring regions we would probably have run a high risk of substantially overstating impacts of scenarios. The methods for disaggregating the agricultural sector and constructing the water I/O table can, given similar data availability, more confidently be applied in other contexts.
- The ratio of economic impact to water demand (Figure 2) can be interpreted as follows: when confronted with high barriers to water use (total depletion, high water tax), farmers tend to give up farming. In these cases the economic consequences are high in relation to

changes in regional water demand. However, the introduction of a low water tax prompts a significant number of farmers to change land use instead of abandonment. As a consequence, reductions in water use are obtained, resulting in about 10% lower impact on the regional economy per unit of water saved than under a higher water tax scenario. Potential water savings are impressive: a low water tax can reduce total water demand by almost 50% at a 7% cost to the regional economy. Important gains can be achieved in setting the water tax level right: significant water savings can be achieved at relatively low expense to the regional economy by incentivising self-organizing capacity of the agricultural sector. Stronger intervention (through higher taxation) fails to take advantage of this self-organizing capacity and although it may generate higher tax revenues, much of it will be necessary to recover from the inefficiency it created in the first place.

- Given the questionable sustainability of groundwater extraction rates, it is of particular concern that agriculture in Murcia has become so heavily dependent on this finite and dwindling resource. Our results show that without groundwater and IBWT, about two-thirds of the region's agricultural area would be abandoned. Agricultural output would be decimated to less than 5% of its current value. Even the introduction of a low water tax would still lead to about 35% of the agricultural area being abandoned, with an associated loss of more than half of the current output. Whereas our farmer survey using discrete choice scenarios may have led to exaggerated responses, this clearly illustrates how vulnerable respondents feel to uncertainty in water supply. Surprisingly, results of increased water prices (Table 6) have the highest impact on grapes and almonds and olives. This contrasts with the land use decisions elicited from DCI interviews, where horticulture and fruits are the first to be abandoned or switched: perhaps the latter crops are perceived as more sensitive to water shortages.
- Additional water supply through IBWT may lead to a 10% expansion of the agricultural area, with an associated increase in agricultural output of 26-35%. The ratio of economic impact to increased water demand of such an expansion is high (€5.63-5.86 per m^3), suggesting that additional water will be used efficiently and an accelerated growth may result. The economic multiplier is, at 1.75, higher than currently obtained, reflecting the combined effect of water and extra land as production factors. Although this sounds promising, it further increases water-dependency of the regional economy. In addition, the assumption of stable technical coefficients inherent to input-output models might be too optimistic here as land onto which irrigation can be expanded may not be as productive as the currently irrigable area. Strikingly, the farmers' discrete choices may reflect this, with only a minority of grain farmers and slightly over half of olive and almond farmers envisioning land use changes to horticulture and fruits or vineyards.
- The amount of water transferred through the Tagus–Segura IBWT scheme was greatly reduced in 1994/5 and 2005-7 as a consequence of a cap on the transfer if the conceding basin experiences water shortage (Figure 3). In the latter period, the contribution of the IBWT to total irrigation dropped to 8% from 54% in 2002/3. This massive reduction is partly compensated for by increased pumping of groundwater resources. The drop in total irrigation may point at a number of potential issues: a) pumping capacity installed is too low to fully compensate for significant reductions in IBWT water; b) not all areas benefiting from the IBWT can switch to groundwater resources if required; or c) the economic cost of pumping exceeds (€0.12 – €0.54 m^{-3}) by far the price (€0.09 m^{-3}) paid for IBWT water (Tobarra González, 2002). Although a mix of these issues may have occurred, the clear peak of local irrigation clearly suggests that a sizable number of farmers have been willing to pay an additional €0.03 to €0.36 per m^3 water. This is in good agreement with our field data.
- Currently, the economy of Murcia produces €39.26 per m^3 of water used – over 8 times as efficient as would be achieved with new IBWT development. As a consequence, the regional economic output per cubic metre of water would drop below €30. Compare that with the over €90 per m^3 that results from the low water tax and it is clear that better alternatives are available. Admittedly, the first option leads to regional economic growth of 4.4% while the latter to a contraction of 6%, but intermediate solutions should be available that warrant growth while improving water use efficiency.

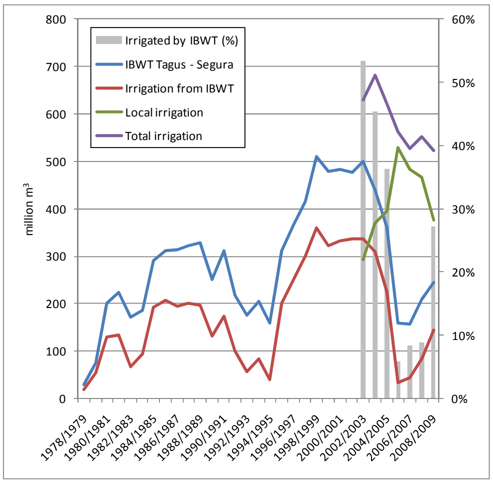

Figure 3. Historical data of water obtained from inter-basin water transfer Tagus–Segura. Source: CREM (2010).

5. Conclusion

Agriculture in the Region of Murcia has increasingly become dependent on blue water resources. Current water availability for irrigation is threatened by continuous overexploitation of groundwater resources, increased competition from non-agricultural (and in some cases illegal) uses, and conflicts over inter-basin water transfer – all in the context of global environmental change. The regional government has a tremendous challenge to reduce overexploitation of water resources and reduce vulnerability of the regional economy to water scarcity. At the same time, the region's farmers feel trapped in water-dependent productivity and fear any reform that negatively affects their resource base. We evaluated the effects of farmers' responses to discrete choice scenarios on the regional economy and water demand by means of input-output modelling. Our results confirm that agriculture is heavily dependent on blue water resources, and farmers see no option to continue farming if confronted with complete water depletion (physical water scarcity) or high levels of water taxation (economic water scarcity). These scenarios would lead to very large reductions in water use by agriculture, but also result in a contraction of the regional economy by more than 13%. A low water tax scenario indicated that some farmers may change land use as a result. Although still leading to a contraction of the regional economy by 7%, this scenario showed that the agricultural sector has a self-organizing capacity to deal with some of its water use inefficiency. Any water tax reform should take stock of this capacity and create synergy between incentives for water use efficiency and government intervention. Resolving water scarcity through new IBWT development may lead to regional economic development (4-5%) but only increases the region's dependency on water. By linking survey-based data from individual land users and an input-output model, a regional impact analysis can be performed. In doing so, we were able to show that although water taxation only has relatively minor effects on product prices, it has the potential to lead to dramatic land use changes with considerable economic impact. Likewise, considerable environmental benefits seem within reach as reduced water use in the economy will benefit areas of ecological importance and might replenish some of the depleted groundwater resources, which could be crucial to prepare for future environmental change.

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Appendix D:

Afforestation, land abandonment and agricultural intensification: Competing trajectories in semi-arid Mediterranean agro-ecosystems

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Paper submitted for publication.

ABSTRACT
An understanding of land use change and its drivers in semi-arid Mediterranean agro-ecosystems is important for informing ways to sustainably manage these systems in responding to future environmental and socioeconomic pressures. In this paper we mapped and quantified land use changes in the semi-arid Mediterranean agro-ecosystem of Torrealvilla catchment (266 km^2) by digitising land use maps from aerial photographs for 1956, 1986, 2004, and 2008. Subsequently we calculated a set of spatial metrics for each of the maps to examine landscape fragmentation. We examined the relationship between each of the observed land use change trajectories and a set of biophysical factors using General Additive Models (GAMs). Finally we qualitatively evaluated the role of socioeconomic drivers on the identified land use change trajectories. The study provides accounts of multidirectional land use trajectories in semi-arid Mediterranean landscapes. Our analysis shows that more than 72% of the study area has undergone significant changes over the past five decades with pronounced effects on landscape composition and structure. Both biophysical and socioeconomic factors are strongly related to the observed spatial and temporal changes in land use. Three major trajectories were observed. Firstly, rain-fed agriculture is becoming less dominant; future abandonment should be anticipated. Secondly, expansion of forested areas is evident in higher altitudes and is characterised by vegetation successions of open to dense forest, as well as the transformation of shrubland into open forest. The trend is still likely to continue given the possibility of further abandonment of rain-fed farming and existing subsidies for reforestation of arable land. Thirdly, intensification has been observed involving the conversion of rain-fed agriculture into irrigated horticulture, grape cultivation, pig/animal farming. This intensification process has occurred mainly in lower parts of the landscape on flat to gentle slopes and near main roads. Further intensification is likely to be subject to market drivers, irrigation water availability, and policies on agriculture and rural areas. Overall, the study shows that even within a given locality contrasting land use trajectories can emerge as a result of local responses to multiple drivers. For a sustainable future management, governmental interventions must therefore fully consider the local spatial and socioeconomic heterogeneity.

Appendix E:

Exploring effects of rainfall intensity and duration on soil erosion at the catchment scale using openLISEM – Prado catchment, SE Spain

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Abstract

In semi-arid areas high-intensity rainfall events are often held responsible for the main part of soil erosion. Long-term landscape evolution models usually use average annual rainfall as input, making the evaluation of single events impossible. Event-based soil erosion models are better suited for this purpose, but cannot be used to simulate longer timescales and are usually applied to plots or small catchments. In this study, the openLISEM event-based erosion model was applied to the medium sized (~50 km^2) Prado catchment in SE Spain. Our aim was to (i) test the model's performance for medium sized catchments; (ii) test the ability to simulate four selected typical Mediterranean rainfall events of different magnitude, and (iii) explore the relative contribution of these different storms to soil erosion using scenarios of future climate variability.

Results show that due to large differences in the hydrologic response between storms of different magnitudes, each event needed to be calibrated separately. The relation between rainfall event characteristics and the calibration factors might help in determining optimal calibration values if event characteristics are known. Calibration of the model features some drawbacks for large catchments due to spatial variability in K_{sat} values. Scenario calculations show that, although ~50% of soil erosion occurs as a result of high frequency, low intensity rainfall events, large magnitude, low frequency events potentially contribute significantly to total soil erosion. The results illustrate the need to incorporate temporal variability in rainfall magnitude-frequency distributions in landscape evolution models.

1. Introduction and objectives

In semi-arid South-East Spain, total rainfall is generally low (~300 mm/y), but very variable and unevenly distributed over the year with rainfall events occurring mainly in spring and autumn (Navarro Hervás, 1991, Bracken *et al.*, 2008). Future soil erosion depends, among other factors, on future temporal rainfall patterns and as such will be affected by climate variability. Projections of climate variability generally predict a decrease in precipitation in the subtropics, but an increase in rainfall intensity and longer periods between rainfall events (Christensen *et al.*, 2007, Meehl *et al.*, 2007, Giorgi and Lionello, 2008). Given the relative importance of extreme rainfall events for erosion and sediment export, simulation studies are required to assess the implications of climate change for soil erosion.

It is our objective in this study, as a first step towards including event information into LEMs, to apply an event-based model to a medium sized catchment and evaluate its performance for simulating rainfall events of different magnitudes and to assess the contribution of rainfall events of different magnitude and frequency to total annual soil loss.

In this study, a new open source version of LISEM (openLISEM[3]) is applied to the ~50 km^2 Prado catchment, located in SE Spain. Our specific aims were

[3] Please find openLISEM at: http://sourceforge.net/projects/lisem/

i) to test the performance of the openLISEM model for simulating erosion and deposition in a relatively large catchment;
ii) to test the model's ability to simulate storms of different magnitudes of rainfall intensity and duration; and
iii) to explore the relative contribution of the different magnitude storms to erosion using scenarios of possible future climate variability.

2. Research area

The study was conducted in the semi-arid region of South-East Spain. The Prado catchment forms a tributary of the Rambla Torrealvilla, upper Guadalentín river, upstream of the town of Lorca in Murcia Province (Fig. 1; UTM 30N 614800; 4171000).

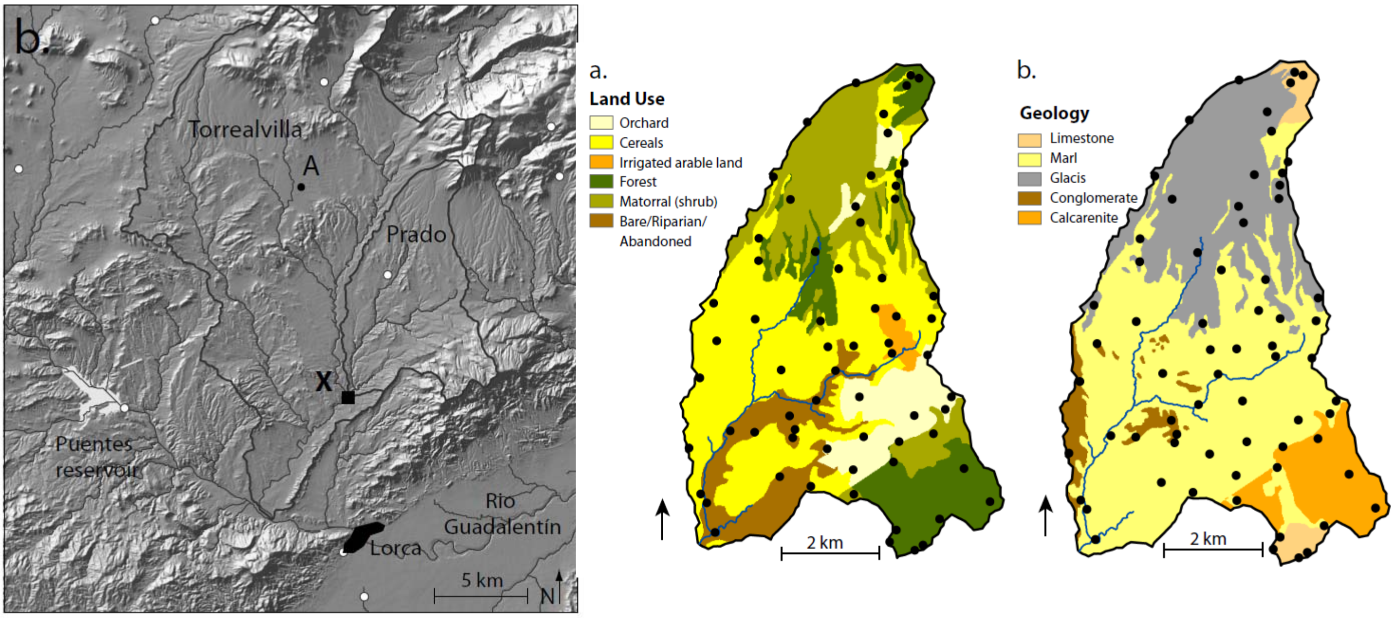


Fig 1: Location of the study area with Prado catchment indicated. X = location of discharge and rainfall measurement devices at Prado outlet; A = Alhagüeces rainfall station; white dots are other rainfall stations used for this study. Left: CORINE Land use map (a) and geology map (b) of the Prado catchment with major ramblas indicated. Black dots are measurement and sampling locations.

3. Methods

The openLISEM model is a physically based runoff and soil erosion model, based on the original Limburg Soil Erosion Model (LISEM) (De Roo *et al.*, 1996b, Jetten and De Roo, 2001). It simulates runoff and erosion during and immediately after a rainfall event. Maps with a cellsize of 20m were used and the calculation timestep *dt* was set to 15s. The channel option of openLISEM is used in this study to represent the permanent gullies occurring in the area.

Rainfall and discharge data for the period 1997 – 2006, measured during the EU MEDALUS projects (Brandt and Thornes, 1996) by the University of Leeds and others at the confluence of the Rambla de Prado and the Rambla Torrealvilla (indicated with X in Fig.1b) were used in this study. This ten-year rainfall record was analysed. Consecutive rainfall was considered a rainfall event if the following criteria were met: >2.4 mm/h intensity at some stage during the event; and <60 min time between recorded rainfall, i.e. if there was no additional rainfall for over an hour, the event is considered to have ended. Furthermore, events must have >5 mm total rainfall and >30min total duration. This resulted in a selection of 94 rainfall events recorded between 1997 – 2006. We classified the events according to a combination of three event characteristics: maximum precipitation intensity (P_{max}; mm/h), total precipitation (P_{tot}; mm) and total duration (T; min). Classification was based on the ratio (P_{max} * P_{tot}) / T, hereafter called 'Event Index' or EVI. A high EVI represents an intense rain storm of short duration and high peak intensity, while a low EVI indicates events with low intensities but long duration. Based on the EVI, four rainfall events of different intensity and duration were selected from the

1997 – 2006 record and further used in this study (18 June 1997 as extreme event; 17 October 2003; 29 September 1997 and 9 December 2003).

To evaluate the effects of different magnitude rainfall events on discharge and soil loss, several model scenarios were calculated. Each scenario includes increasingly more extreme events but similar total annual rainfall, as such reflecting a range of possible future climate scenarios for the coming century.

4. Results

The selected events have distinct event characteristics, as shown in Table 1 (total and maximum precipitation and event duration), resulting in different Event Indices (EVIs).

Table 1: Event characteristics for the four selected events from the 1997-2006 period, and the 28 September 2009 event

	18 June 1997	*17 Oct 2003*	*29 Sept 1997*	*9 Dec 2003*	*28 Sept 2009*
Total rainfall (mm)	62.8	32.0	19.4	43.3	16.8
Peak rainfall (mm/h)[a]	171.2	117.4	46.1	15.4	18.2
Total duration (min)	65	110	145	710	370
Peak discharge (l/s) [b]	13070	2989	920	466	-
Total discharge (m^3) [b]	31422	14920	3508	3217	-
Event Index (EVI)	165.4	34.2	6.2	0.9	0.8

[a] *Maximum average intensity over a 5-min interval*

[b] *Not given for the 28 Sept 2009 event, as only two discharge measurements are available*

Fig. 2 shows the measured and simulated hydrographs at the outlet for the four selected events. Fig. 3 shows results from the scenario calculations. The base scenario calculations show that one extreme event causes 42% of total erosion. On the other hand, all small events together cause 51% of total erosion, indicating that, assuming the scenario is representative for longer time spans, about half of the total erosion occurs during low intensity long duration and high frequency events.

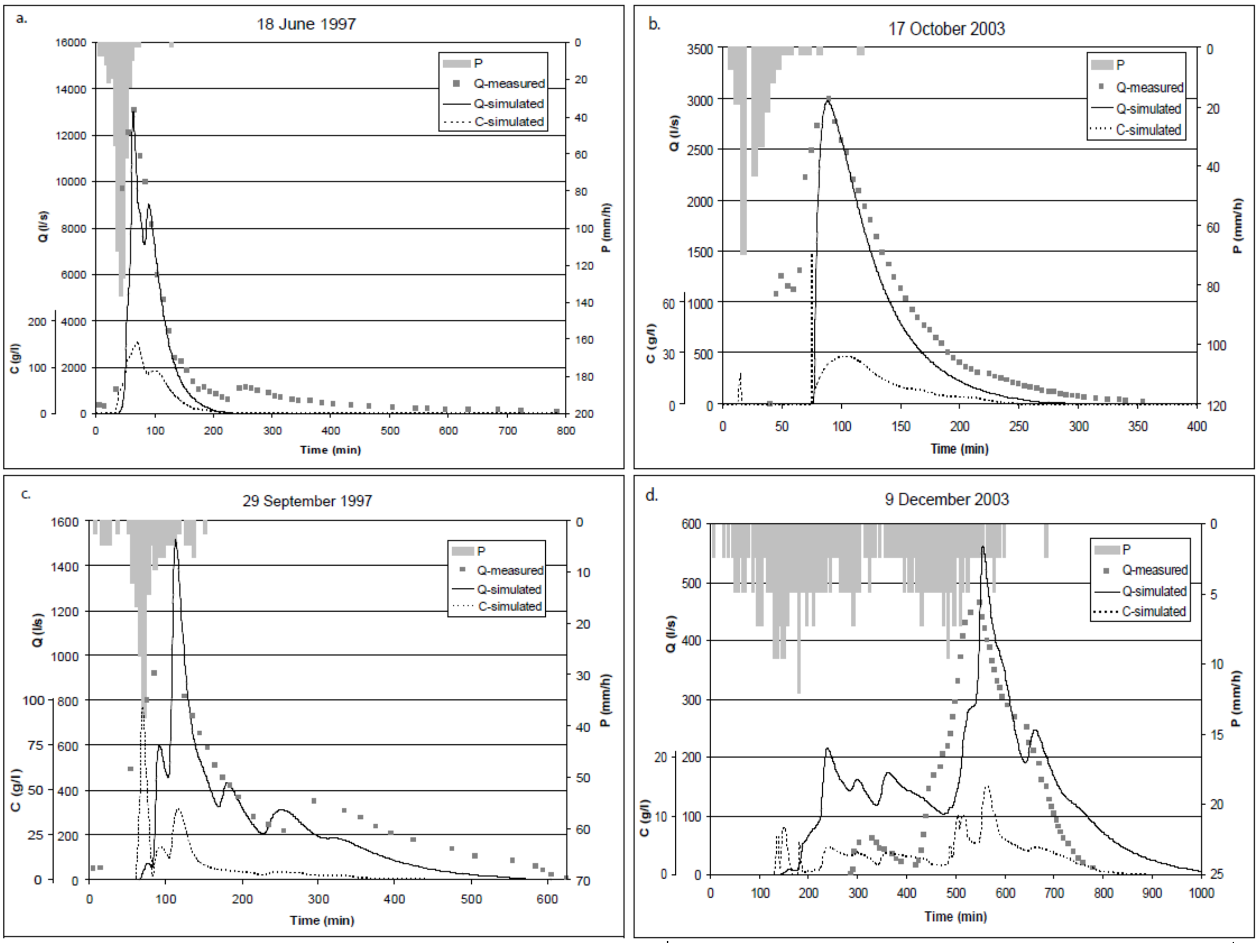


Fig. 2: Precipitation (P, right axis), discharge (Q, 2nd left axis) and sediment concentration (C, 1st left axis) at the Prado outlet for four events: 18 June 1997 (a), 17 Oct 2003 (b), 29 Sept 1997 (c) and 9 Dec 2003 (d). Note differences in scales of axes between the four events.

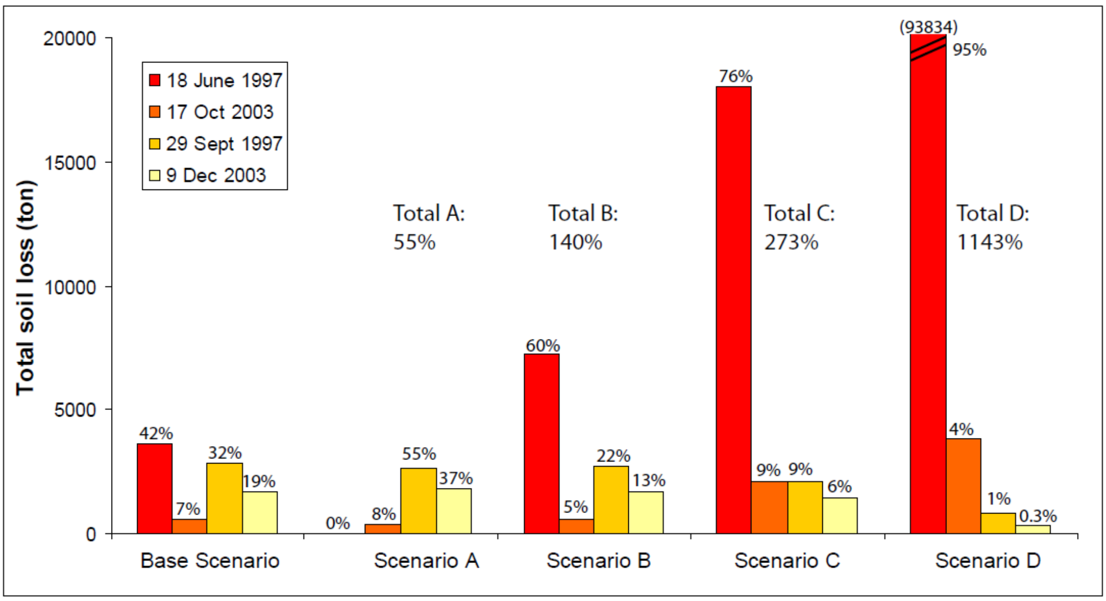


Fig. 3: Total soil loss (tons) at the outlet for the four scenarios with relative contribution per event-type. Total percentages are relative to the base scenario; percentages given for each event-type are contributions of total erosion of that scenario (i.e. they sum to 100% for each scenario).

5. Conclusions

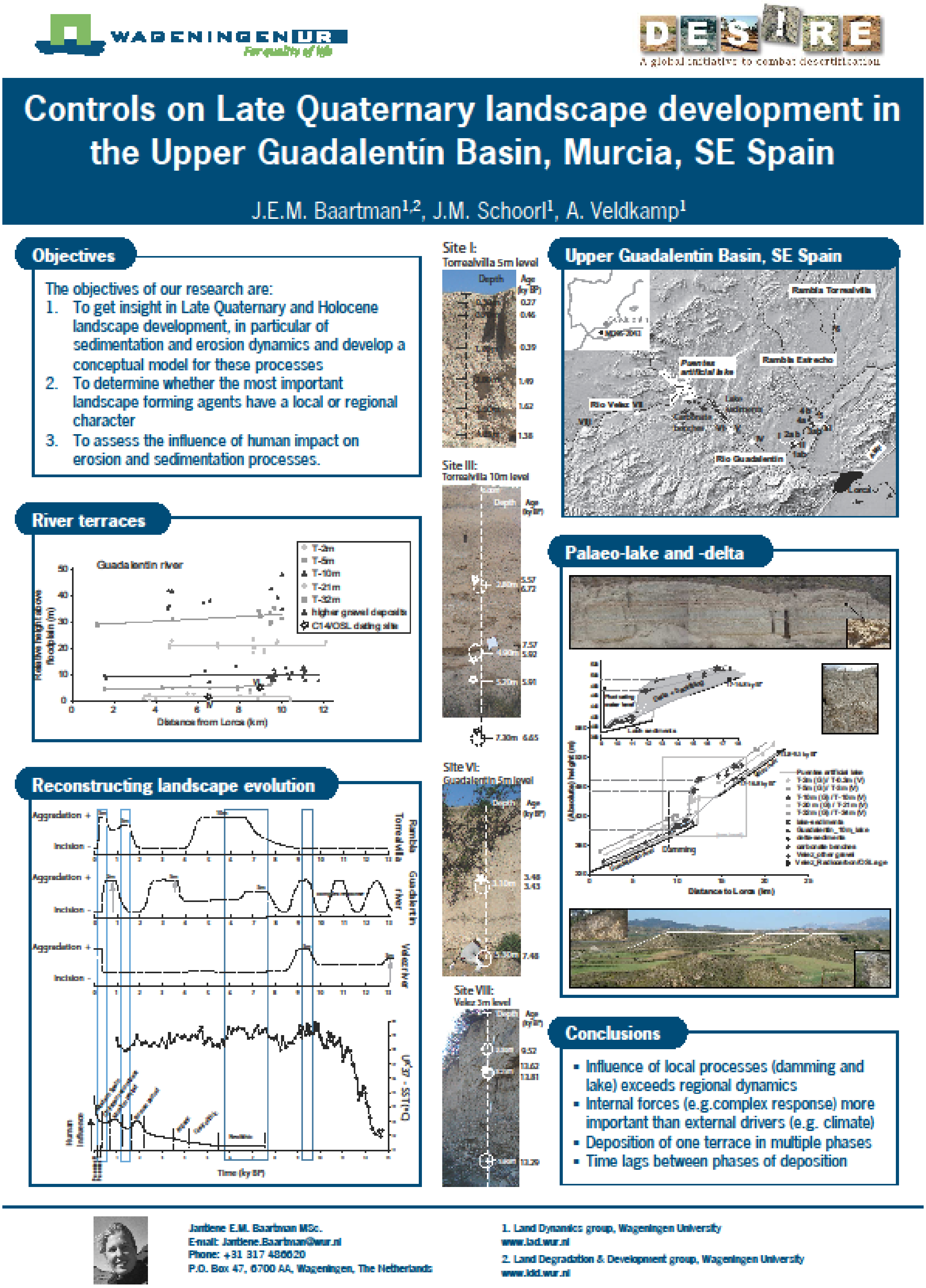
Until now, the event-based erosion model LISEM has been applied to small catchments up to a few square kilometres in size. Our results show that, for a medium sized catchment (~50 km^2), the model is able to simulate storms of different magnitude, but for each event a separate calibration set is needed. The power relation (r^2 = 0.99) between calibrated K_{sat} multiplication factor and Event Index (EVI) might help in determining which values of K_{sat} are optimal for calibration if the event characteristics (maximum and total precipitation and event duration) are known. Using initial literature values of K_{sat} and a multiplication factor for calibration resulted in one land use dominating the simulated hydrograph, resulting in simulated erosion being concentrated in one area and unreliable spatial maps of simulated erosion and deposition. However, average values of erosion for the entire catchment are in the order of measured values in SE Spain. Although the contribution of many small magnitude events is about half of total erosion in the base scenario, the contribution of one extreme event constitutes 42% of total erosion. Thus, although occurring infrequently, high magnitude events potentially contribute much more to total soil loss than lower magnitude events, even though the number of lower magnitude events is much larger. This has consequences for longer-term landscape evolution modelling, in which usually average annual precipitation is used as input for erosion equations. This does not assess the potentially large influence of single events. As the calculated scenarios in this study are a lumped sum of the erosion caused by different events, we could not evaluate interactions between subsequent events. Incorporating the results of event based erosion models in landscape evolution models would make this kind of evaluation possible.

Note: This is a summary of our work. Please see for the entire paper:

Baartman, J.E.M., Jetten, V.G., Ritsema, C.J., De Vente, J., 2011. Exploring effects of rainfall intensity and duration on soil erosion at the catchment scale using OpenLISEM – Prado catchment, SE Spain. *Hydrological Processes*, 2011 DOI: 10.1002/hyp.8196 http://onlinelibrary.wiley.com/doi/10.1002/hyp.8196/abstract

Appendix F:

CONTROLS ON LATE QUATERNARY LANDSCAPE DEVELOPMENT IN THE UPPER GUADALENTÍN BASIN, MURCIA, SE SPAIN



CONTROLS ON LATE QUATERNARY LANDSCAPE DEVELOPMENT IN THE UPPER GUADALENTÍN BASIN, MURCIA, SE SPAIN

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ABSTRACT

Landscapes in South-eastern Spain have developed in response to tectonics, climatic fluctuations and, more recently, to human action. In the valleys, fluvial and colluvial sediments are found in the form of river terraces, pediments and slope deposits. We studied these sediments to evaluate landscape dynamics and the processes of sedimentation and erosion in the semi-arid region of the Guadalentín Basin, Murcia Province, SE Spain.

The objective of the study is to deduce controls on Late Quaternary and Holocene landscape development. Fieldwork was carried out on the reach of the Upper Guadalentin, upstream of the city of Lorca, and two of its tributaries (Rio Velez and Rambla de Torrealvilla). River terrace levels were mapped using GPS and presence of gravel layers in outcrops. For the Rambla de Torrealvilla, more detailed sediment descriptions show their build-up. Charcoal was found and dated (14C) on ten locations, while 15 samples for Optically Stimulated Luminescence (OSL) dating were taken to have an age-control on processes of sedimentation and erosion. While the OSL dating measurements and analysis are still in process at this time, some preliminary results are given. Several terrace levels are identified along the Rio Guadalentin and the Rio Velez. These have formed in response to regional and/or global changes in climate. However, local mechanisms have played an important role in the area, overruling regional dynamics. From finely layered sediments, it is deduced that a lake existed during some time in the area, caused by a blockage of the valley. This lake was filled in with sediments and a delta was build at its end, interfering with terrace levels. When the blockage was broken through, lake sediments have been removed and after incision, younger terraces have developed. The Torrealvilla tributary is draining the Lorca Basin, and sediments seem to be younger than those along the Guadalentin and Velez rivers. Infilling of the basin and incomplete removal has shaped this valley. Outcrops in the gully sidewall show stacked layers of large to fine gravels and fine sediments with smaller gravel layers in between.

We will present a conceptual model of landscape development since the Late Quaternary based on the age control (14C and OSL) and field observations. This reconstruction is correlated to climatic fluctuations and rates of sedimentation and erosion are approximated on a millennial timescale. Following this approach of longer-term geomorphological investigation of landscape development, we can ultimately put the relative contribution of human actions in the context of natural erosion and sedimentation processes.

Keywords: Landscape development, Guadalentin Basin, Late Quaternary