IRRIGATION VERSUS DESERT IN THE CENTRAL EBRO BASIN

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1. Introduction
1.1. Why this trip?
Spain and other dry countries rely on irrigation to guarantee their agricultural production. One of the aridest lands of Europe is the natural region of Monegros, in the central Ebro valley (North-Eastern Spain). We will visit the Lanaja-Sariñena-Grañén area located in the northern fringe of Monegros. This area, in transition to the more humid region of Pyrenees, has undergone intensive transformations due to the irrigation with water from reservoirs built outside the area, in the Pyrenaic rivers.

The aim of our trip is to show: (i) the landscape and social changes produced by irrigation and the associated works, (ii) the agricultural response of typical soils or geological materials to irrigation, and (iii) some cases of soil degradation related to the irrigation.

1.2. Geology and geomorphology
Synthetic explanations of the geology of the Ebro Basin can be found in Riba et al. (1983) and in Pardo (2004). Figure 1 shows the map of Tecto-Sedimentary Units of the Ebro Basin, taken from Pardo (2004). More details can be found in the geological maps at 1:50000 published by Instituto Geominero de España (serie MAGNA).

Figure 1. Map of tecto-sedimentary units (T1 to T8) of the Cenozoic Ebro basin (after Pardo et al., 2004).
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The rocks of the visited area are sedimentary. The sediments were deposited during the Miocene, in an endorheic continental regime. The upper sediments are in the top of the Sierra de Alcubierre, which we will cross in our way from Zaragoza to the visit area. The stratigraphy and sedimentology of this region was established by Quirantes (1978). In the visited area, roughly horizontal strata of lutite, sandstone and limestone alternate in variable proportions (Fig. 2) related with their central or lateral location at the time of deposition. These rocks often contain highly soluble salts, mainly sodium chloride. The gyprock is not very frequent in the visited area, outcropping as small intercalations only in some locations.

Figure 2. Miocene horizontal strata of lutite, sandstone, and limestone alternating in variable proportions in the visited area.

The basin opened to the Mediterranean throughout the Ebro river at the end of Miocene. This event was the beginning of a general erosive period, with local episodes of alluvial and colluvial deposition during the Quaternary, leading to the present relief.

The outstanding landforms in the visited area are mesas of very variable extent, ranging to buttes, often with steps in their slopes, caused by resistant sandstone strata. Some escarpments are vertical because of the occurrence of sandstone paleochannels, and rock-fall in the hill slopes also occurs. Less frequent are limestone strata, with decimetric or centimetric depth, often topping small mesas.

The Quaternary fluvial deposits, studied by Rodríguez Vidal (1986) appear in several levels of terraces associated to the main rivers. The terraces are formed by different proportions of rounded Mesozoic and Eocene gravels (limestone sandstone, and quartzite) with variable proportions of silt. The higher levels of terraces can be cemented by calcium carbonates forming calcic or petrocalcic horizons. Other fluvial Quaternary deposits are: degraded glacis, alluvio-colluvial deposits, and deposits of the valley bottoms.

Rodríguez-Ochoa et al. (2000) established five Quaternary units: (i) coarse detritic sediments (gravels and stones in a silty-clay matrix), related with the piedmont of the Sierra of Alcubierre; (ii) polygenic coarse detritic sediments (stones and gravels, river terraces); (iii) fine detritic sediments (sand, silt, and clay with gravels), alluvial fan of first terrace in the Flumen river; (iv) fine detritic sediments
(sand, silt, and clay with gravels, bottom valleys), mixed materials of alluvial and colluvial origin; (v) fine-grained laminated detritic sediments (clay and silt), a material overspread in the Ebro valley, named “hojaldre” by Herrero et al. (1989, page 25) and studied by these authors, by Rodríguez et al. (1989, 1990), and by García-González et al. (1996).

A comparison of the chemical properties of lutites and hojaldre in the study area can be established from the data published by Rodríguez-Ochoa et al. (2000) about 30 samples of fresh lutites and 9 samples of hojaldre. The data of these authors about the sodium adsorption ratio, i.e., $\text{SAR} = \frac{\text{Na}^+}{\left[(\text{Ca}^{2+} + \text{Mg}^{2+})/2\right]^{0.5}}$, and the electrical conductivity of the saturation paste extract ($\text{CEe}$) are shown in graphical form in Figure 3. Soils with $\text{CEe} > 8$ dS/m are strongly saline, with relevant yield descent excepted some few tolerant crops. Values of $\text{SAR} > 13$, corresponding to exchangeable sodium percentage (ESP) $> 15$, can affect crop development; moreover these high ESP allow clay dispersion that can make impervious the soil, with water ponding, pipe-drain clogging, piping, etc. The relative descent of $\text{CEe}$ from lutite to hojaldre, accompanied by an increased $\text{SAR}$, and an overall increase of pH in the saturated paste from around 8.5 in lutites to around 9.5 in hojaldre (see the same authors) gives to hojaldre the worst prognostic for irrigated agriculture in the visited area. Moreover, the vertical water transmissivity is very low.

Elevation in the visited area ranges from 400 m to 250 m above the sea level. Several geomorphic units were distinguished and mapped by Rodríguez-Ochoa et al. (2000). For the visit area the main landforms are: platforms, fluvial terraces, slopes, and bottoms. Some platforms are structural, topped by limestone or sandstone, but the most frequent are the residual platforms, locally named “sasos” (from Latin saxetum, stony). Some of these residual platforms, covered by fluvial gravels, are remnants of old river terraces; other residual platforms, covered by alluvio-colluvial Plioquaternary deposits with less rounded stones, are isolated remnants of ancient glacis. The terraces of the river Flumen are constituted by sandy and silty materials, with gravels in variable amounts. The slopes are the connexion between flat landforms (platforms, terraces, bottoms) of different elevation; in general the Miocene rock is covered by shallow Quaternary material; some of the steep slopes are covered by stones (rock-fall) and are locally named “canteras”. We consider bottoms all the areas of lower...
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elevation than the surrounding landforms, flat-bottomed valleys (locally named vales) and depressions, which receive materials from the conterminous landforms.

1.3. Climate

Aridity is the most prominent feature of climate in the central Ebro valley. Authors from different disciplines (Braun-Blanquet and Bolòs, 1957; Dregne, 1976) have related the aridity to factors like: the many sunshine hours during the year, the scarce and irregular precipitation, and the “cierzo”, a strong and dry NW wind blowing mainly in autumn and winter. The similarity with the African deserts in satellite images was early noted (Hasser, 1966; Short et al., 1976). The aridity of the central Ebro valley is higher than in other locations of lower latitude around the world, after the agricultural water deficits (Table 1) calculated by Herrero and Snyder (1997).

Table 1. Annual mean daily temperature (Tmean), mean monthly cumulative reference evapotranspiration (ET0), precipitation (P), and ET0 - precipitation. The locations are ranked by increasing water deficit (last column). Taken from Herrero and Snyder (1997).

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Elevation</th>
<th>Tmean</th>
<th>ET0</th>
<th>P</th>
<th>ET0-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco, Calif.</td>
<td>37° 37’ N</td>
<td>3</td>
<td>13.7</td>
<td>890</td>
<td>501</td>
<td>389</td>
</tr>
<tr>
<td>Brindisi, Italy</td>
<td>40° 40’ N</td>
<td>28</td>
<td>16.8</td>
<td>1141</td>
<td>644</td>
<td>497</td>
</tr>
<tr>
<td>Seville, Spain</td>
<td>37° 22’ N</td>
<td>9</td>
<td>18.8</td>
<td>1159</td>
<td>564</td>
<td>595</td>
</tr>
<tr>
<td>Casablanca, Morocco</td>
<td>33° 34’ N</td>
<td>62</td>
<td>17.8</td>
<td>1076</td>
<td>426</td>
<td>650</td>
</tr>
<tr>
<td>Tunis, Tunisia</td>
<td>36° 50’ N</td>
<td>4</td>
<td>18.3</td>
<td>1159</td>
<td>443</td>
<td>716</td>
</tr>
<tr>
<td>Santiago, Chile</td>
<td>33° 27’ N</td>
<td>520</td>
<td>14.9</td>
<td>1125</td>
<td>335</td>
<td>790</td>
</tr>
<tr>
<td>Athens, Greece</td>
<td>37° 58’ N</td>
<td>15</td>
<td>18.3</td>
<td>1242</td>
<td>402</td>
<td>840</td>
</tr>
<tr>
<td>San Diego, Calif.</td>
<td>32° 44’ N</td>
<td>4</td>
<td>17.6</td>
<td>1119</td>
<td>237</td>
<td>882</td>
</tr>
<tr>
<td>Almeria, Spain</td>
<td>36° 50’ N</td>
<td>6</td>
<td>18.0</td>
<td>1235</td>
<td>233</td>
<td>1002</td>
</tr>
<tr>
<td>Fresno, Calif.</td>
<td>36° 46’ N</td>
<td>100</td>
<td>17.0</td>
<td>1297</td>
<td>267</td>
<td>1030</td>
</tr>
<tr>
<td>Zaragoza, Spain</td>
<td>41° 39’ N</td>
<td>237</td>
<td>14.9</td>
<td>1406</td>
<td>337</td>
<td>1069</td>
</tr>
<tr>
<td>New Delhi, India</td>
<td>28° 35’ N</td>
<td>216</td>
<td>25.2</td>
<td>1796</td>
<td>692</td>
<td>1104</td>
</tr>
<tr>
<td>Giza, Egypt</td>
<td>30° 08’ N</td>
<td>19</td>
<td>20.9</td>
<td>1673</td>
<td>19</td>
<td>1654</td>
</tr>
</tbody>
</table>

The visited area is less arid than the central Ebro valley. The records from 1968 to 1990 in the weather station of Almuniente, at 357 m of elevation, located at the North of the visited area are used to characterize the climate; the mean annual temperature is 13.8 °C, and the mean annual precipitation is 474.5 mm. Martínez-Cob et al. (1998) estimated for this station a mean annual reference evapotranspiration (ET0) of 1221 mm. An agricultural water deficit of 600 mm is calculated by subtracting this ET0 affected by the factor 0.88 calculated by Faci et al. (1994), from the mean annual precipitation. The corresponding monthly mean volumes of precipitation and ET0 are shown in Figure 4.

The soil climate is here described with the concepts and criteria of Soil Survey Staff (1999), in spite of the lack of local measurements. The soil temperature regime is thermic. According to Rodríguez-Ochoa et al. (2000) and Nogués (2002), the soil moisture regime is considered aridic in soils whose available water holding capacity until 1.5 m depth or until lithic or paralithic contact (AWHC1.5) is ≤
50 mm, and xeric if AWHC1.5 is > 50 mm. The coarse elements content of the soil must be taken in to account when establishing AWHC both from laboratory determinations in the fine earth of soil samples and from pedotransfer rules (Nogués et al. 2000).

Figure 4. Mean monthly precipitation (dashed line), and the calculated monthly ET₀ affected by the correction factor 0.88 (solid line) from records of the Almuniente weather station in Aragón, Spain.

1.4. Soils
Folk knowledge in the visited area distinguished several kinds of soils as well as soil or landscape features, often these distinctions are based on agricultural properties and on the behaviour against irrigation. Most of these concepts are intermingled with the folk perception of landscape and vegetation. Examples are the following household words: aguazibera, buro, cantera, cascallo, chamarcal, chulla, clamor, clota, coscarana, demba, encarao, esterza, estrocar, filada, garroz, gleral, lastra, lera, mallacán, mallada, manantio, ontinar, polpa, reguero, salagón, salobrar, sarda, saso, secativo, sosal, tollo, torraco, troco, val, valpodrida, varella, zaborro, zinglo. Some of these words persist only in the toponymy, in aragonese dictionaries like Andolz (1992), or in specific linguistic publications (Castañer, 1983). Many of them and the corresponding concepts have been lost with emigration in the XX Century and with the conversion of the remaining population to urban or industrial values; moreover toponyms are often disregarded or corrupted in the detailed maps drawn with modern technologies.

The soils and their relationships with geomorphology in the visited area have been studied by Rodríguez-Ochoa et al. (2000). Following these authors and using the Great Groups of soils provided by Soil Survey Staff (1999), the structural platforms have Torriorthents and some Haplocalcids. The dominant soils in the residual platforms are Petrocalcids, Haplocalcids, Xerofluvents, and Xerepts, accompanied by Torriorthents, Xerorthents, Haploxeralfs, Petroargids and Calciargids, with presence of Oxyaquic Xerofluvents and Oxyaquic Xerorthents. The dominant soils in the slopes are Xerofluvents, Xerepts, and Torriorthents, while in the bottoms the dominant soils are Xerofluvents, including Oxyaquic Xerofluvents and spots of Gypsic Haploxerepts.

Three examples of representative soil profiles in the visited area are shown in Figures 5 to 7, with their analytical data (Tables 2 to 4) taken from Noguès (2002).
Geomorphic unit: *Platform*

**Soil Series: Torraza**

Soil Taxonomy System
(Soil Survey Staff, 1999):
*Loamy-skeletal, mixed, active, thermic, shallow Calcic Petrocalcid*

World Reference Base for Soil Resources
(FAO, 1998):
*Endopetric-Endoskeletal Calcisol*

Figure 5. Typical soil developed on a residual platform. The petrocalcic horizon is at 40 cm. These soils were not disturbed by levelling, and give good production under irrigation.

Table 2. Analytical data of the soil profile BA15 (Torraza Series), shown in Figure 5.

<table>
<thead>
<tr>
<th>Genetic horizon</th>
<th>Depth (cm)</th>
<th>Coarse fragments &gt; 2 mm (%)</th>
<th>pH water 1:2.5</th>
<th>EC 1:5 (dS/m 25°C)</th>
<th>Organic matter (%)</th>
<th>equivalent calcium carbonate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>00-25</td>
<td>16-35</td>
<td>8.4</td>
<td>0.12</td>
<td>1.5</td>
<td>24.7</td>
</tr>
<tr>
<td>Bwk</td>
<td>25-38</td>
<td>36-70</td>
<td>8.5</td>
<td>0.14</td>
<td>1.0</td>
<td>27.7</td>
</tr>
<tr>
<td>Bkm</td>
<td>38-&gt;60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Ø μm</th>
<th>Silt Ø μm</th>
<th>Clay Ø μm</th>
<th>Textural class (USDA)</th>
<th>Cation-exchange capacity (meq/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 to 50</td>
<td>50 to 02</td>
<td>&lt; 2</td>
<td>sandy clay loam</td>
<td>9.4</td>
</tr>
<tr>
<td>49.23</td>
<td>23.64</td>
<td>27.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50.51</td>
<td>26.66</td>
<td>22.83</td>
<td>sandy clay loam</td>
<td>9.7</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Geomorphic unit: Slope

Soil Series: Salagones

Soil Taxonomy System
(Soil Survey Staff, 1999):
Clayey, mixed, subactive, calcareous, thermic, shallow Oxyaquic Xerorthent

World Reference Base for Soil Resources
(FAO, 1998):
Eutric-Calcaric Regosol

Figure 6. Shallow soil developed on lutite. Salinity could limit agriculture, but the flooding for rice cropping can overcome this inconvenient.

Table 3. Analytical data of the soil profile BA5 (Salagones Series), shown in Figure 6.

<table>
<thead>
<tr>
<th>Genetic horizon</th>
<th>Depth (cm)</th>
<th>Coarse fragments &gt; 2 mm (%)</th>
<th>pH water 1:2.5</th>
<th>EC 1:5 (dS/m 25°C)</th>
<th>Organic matter (%)</th>
<th>Equivalent calcium carbonate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap1</td>
<td>00-17</td>
<td>0</td>
<td>8.5</td>
<td>0.58</td>
<td>1.7</td>
<td>32.3</td>
</tr>
<tr>
<td>Ap2</td>
<td>17-35</td>
<td>0</td>
<td>8.6</td>
<td>0.29</td>
<td>1.0</td>
<td>34.8</td>
</tr>
<tr>
<td>Cr</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Textual class (USDA)</th>
<th>Cation-exchange capacity (meq/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>∅ μm</td>
<td>∅ μm</td>
<td>∅ μm</td>
<td>&lt; 2</td>
<td></td>
</tr>
<tr>
<td>2000 to 50</td>
<td>50 to 02</td>
<td>0.02</td>
<td>silty clay loam</td>
<td>3.7</td>
</tr>
<tr>
<td>6.33</td>
<td>58.17</td>
<td>35.50</td>
<td>silty clay loam</td>
<td>4.4</td>
</tr>
<tr>
<td>6.62</td>
<td>57.68</td>
<td>35.7</td>
<td>silty clay loam</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Saturation water</th>
<th>Saturated paste extract (ions in meq/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%)</td>
<td>ECe (dS/m 25°C)</td>
</tr>
<tr>
<td>58</td>
<td>3.43</td>
</tr>
<tr>
<td>48</td>
<td>1.58</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Geomorphologic unit: Bottom

Soil Series: Cordel

Soil Taxonomy System
(Soil Survey Staff, 1999):
Fine-loamy, mixed, semiactive, calcareous, thermic Typic Xerofluvent

World Reference Base for Soil Resources
(FAO, 1998):
Eutric-Calcaric Regosol

Figure 7. Deep soil without coarse fragments developed in a gentle slope. The available holding water capacity is high, and then irrigation can be less frequent than in shallow or in stony soils.

Table 4. Analytical data of the soil profile BA6 (Cordel Series), shown in Figure 7.

<table>
<thead>
<tr>
<th>Genetic horizon</th>
<th>Depth (cm)</th>
<th>Coarse fragments &gt; 2 mm (%)</th>
<th>pH water 1:2.5</th>
<th>EC 1:5 (dS/m 25°C)</th>
<th>Organic matter (%)</th>
<th>Equivalent calcium carbonate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>00-30</td>
<td>0</td>
<td>8.5</td>
<td>0.19</td>
<td>1.3</td>
<td>26.2</td>
</tr>
<tr>
<td>Bw1</td>
<td>30-70</td>
<td>0</td>
<td>8.7</td>
<td>0.21</td>
<td>0.8</td>
<td>26.2</td>
</tr>
<tr>
<td>Bw2</td>
<td>70-&gt;140</td>
<td>0</td>
<td>8.7</td>
<td>0.19</td>
<td>0.5</td>
<td>27.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Ø μm 2000 to 50</th>
<th>Silt Ø μm 50 to 02</th>
<th>Clay Ø μm &lt; 2</th>
<th>Textural class (USDA)</th>
<th>Cation-exchange capacity (meq/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.25</td>
<td>53.58</td>
<td>27.17</td>
<td>silt loam</td>
<td>6.7</td>
</tr>
<tr>
<td>18.59</td>
<td>57.33</td>
<td>24.08</td>
<td>silt loam</td>
<td>6.0</td>
</tr>
<tr>
<td>15.21</td>
<td>53.85</td>
<td>30.93</td>
<td>silty clay loam</td>
<td>7.1</td>
</tr>
</tbody>
</table>
1.5. Irrigation and agriculture

The term aridic quantitatively defined in Soil Survey Staff (1999) can be translated in plain agricultural terms as: by average, seven years on ten, non-irrigated barley (the cereal with less water requirements) can not reach full development, and yield is nil. Moreover, bad agricultural years occur in strings. Irrigation is a must for agricultural production in the central Ebro valley. Roman inscriptions older than 2000 years have noticed that irrigation in alluvial plains was practised by pre-Roman settlers (Fatás and Beltrán, 1997). For centuries, irrigation was confined in the river terraces. Now, irrigated lands cover around 8000 km² of the total surface of the Ebro valley 85362 km² and new irrigation districts are in progress or planned (Figure 8).

Figure 8. Irrigation is significant in the central Ebro valley, where drylands are unproductive or desertic. Old irrigated lands are fringes in the rivers. The new irrigated districts are mainly in the Northern part of the valley because water comes from reservoirs in the Pyrenean rivers.

The advances in water storage, conduction, and distribution allowed the irrigation of lands having different geological, geomorphic, and pedological conditions. Flood was the only available technology for water application until the 70’s of the XX century, thus land levelling was a must, producing strong landscape modifications from 1940 to 1975 when broad new irrigated districts were built in the Ebro valley. Moreover, the size and shape of plots for basin and border irrigation must be adapted to the water distribution network capacity. The most frequent size of irrigated plots is < 1 ha (Figure 9) in the visited irrigated lands. The soil profiles in slopes and bottoms were disturbed, mixing the shallow A horizons with underlying materials like the saliferous lutite or the highly sodic hojaldre. This fact plus the seepage from the irrigated platforms (Figure 9 and 10) is the main responsible for salt redistribution in the irrigated lands leading to salt evapoconcentration in the unvegetated areas.
and in the non-irrigated soils. The redistribution of salts also occurs in non-irrigated lands (Figure 11), and saline soils were present before the irrigation, as denoted by the presence of halophytes in closed depressions or other humid enclaves (Braun-Blanquet and Bolós, 1957; Herrero, 1982). The water requirements of the crops are several times the average precipitation and moreover a surplus of irrigation water is needed to maintain the salts out of the root zone, so the salts movement is exacerbated by irrigation.

Figure 9. The ortophotograph of an irrigated area built around 1955 shows the intensive land-forming and the size and shape of plots. In the right, other more recent irrigated area cultivated with barley. Note the typical pattern of bare spots due to the original soil destruction for levelling and the saline seepage from irrigation in the upper plots.

Figure 10. Sketch of the changes following the creation of plots for basin and border irrigation in the central Ebro valley (Herrero and Aragüés, 1988). Evaporation (straight arrows) concentrates in the soil those salts dissolved by seepage (curve
arrows) in the Miocene strata. Drainage ditches are needed to intercept water flows and to conduct them, together with surplus and other waters, to the rivers.

![Image](image.png)

Figure 11. This small “val” (a flat-bottomed valley) is not influenced by irrigation as shown by rainfed almond and olive trees in the platform, and by xerophytes covering the slope. Notwithstanding, efflorescences in the footslope and the helophyte Phragmites communis in the small ravine of the bottom denote water and salts redistribution.

Some soils in the bottoms or in gentle foot slopes are saline or saline-sodic, and remained uncultivated for years after the arrival of irrigation. Many of these lands are now paddies provide that, in the current market conditions, rice is a profitable crop. Paddies remain under a running water table, from the end of April until September, and rice is harvested in October. In many cases the paddy is dried for some days in the middle of the crop cycle, in order to control the algae. Rice is by far the most water requiring crop in the Ebro valley, with an estimated average irrigation water application over 15000 m³ by ha and year (Tolosa, 1990). Water shortage in the Canal of Monegros in dry years, like 2005, results in the reduction of the number of paddies. Rice, a non salt-tolerant plant, can be cultivated because of the low salinity of the irrigation water and the relative independence from soil salinity or sodicity, archived by paddling mud with rice stubble producing an impervious and continuous soil layer. Rice roots attain only up to 15 cm depth, and do not penetrate this impervious layer. All the rice cycle, from seedling to harvesting is fully mechanized. Anane et al. (2001) have studied the distribution of paddies in the visited area, as a first step to investigate the on-site and the off-site environmental effects of rice cropping.

In the last 30 years, the new irrigation districts are designed with pressurized irrigation (sprinkling and drip); moreover, pumping technology and cheap energy result in a non-dependence of gravity for water distribution and application. This new irrigation technology is often reputed as less soil disturbing than flood irrigation. In the already flood-irrigated lands, the installation of pressurized irrigation has to erase the old plots to facilitate either the use of big machinery or the running of central pivots and lateral machines for sprinkling.

In the visited area, the irrigation districts built after 1930 are irrigated from the Canal of Monegros and Canal of Cinca, with water from the reservoirs in the Pyrenees. Table 5 shows the composition of
a sample of this irrigation water at the moment of its application to a plot. The low electrical conductivity denotes the good quality of this water for plant growth, however the low calcium content of the irrigation water can lead to sodification of those soils lacking of gypsum in their profile. The saline flows from irrigated lands, are related with the increasing salinity of the rivers in the Ebro valley in the last decades (Aragüés et al., 1996). A recent work (Herrero and Pérez-Coveta, 2005) quantifies the decrease from 1975 to 1999 of the salinity and sodicity in the upper meter of irrigated agricultural soils in the visited area.

Table 5. Typical chemical characteristics of the irrigation water from the Monegros Canal. Ions are in meq/L.

<table>
<thead>
<tr>
<th>Electrical conductivity dS m⁻¹ at 25º</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>Na⁺</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>CO₃²⁻</th>
<th>HCO₃⁻</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>1.5</td>
<td>0.5</td>
<td>0.89</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>2.0</td>
<td>0.89</td>
</tr>
</tbody>
</table>

In the last years, many irrigated districts built before 1970 are involved in a modernization process, changing from basin and border irrigation to pressurized irrigation. The National Plan for Irrigated Lands (Plan Nacional de Regadíos, 2002) approved by the Spanish Government will act in a first step (until 2008) on 1.13 million hectares investing 5024 million euros, with a 60% by the Government. This Plan includes the change of flood to pressurized irrigation in 730901 ha. The targets for this change are: to achieve a more efficient water use, to reduce the mobilization of salts and agrochemicals, to alleviate manpower shortage, and to increase the competitiveness of crops production. In this change, the energetic dependence of pressurized irrigation is often disregarded.

Nowadays as in the past, irrigation is perhaps the chief option for a sustainable future for Aragon and other arid regions. In the past, bad years affected the whole society through its main productive and employing sector, the agriculture. This reason plus the prosecution of the nation self-providing of food and the full employment, pointed out to consecutive political regimes the expansion of irrigated surfaces as a social goal. Now, the rural depopulation has been almost accomplished. The ageing and scarcity of the remaining habitants in the drylands hinder the productive uses of these lands. On the contrary, both the old and the new irrigated districts attain to fix a part of the population, and new villages for new irrigators “colonos” were built from 1945 to 1970. More recently, easy transportation and agricultural mechanization have partially voided many of the old and new villages that are evolving to week-end villages.

The overall success of the irrigation is generally accepted, in spite of several problems like soil salinity and sodicity, water logging, pipe-drain clogging, etc. Many of these problems were not foreseen by the designers of the irrigated districts due to the lack of both specific researches and soil maps before the transformations of dry lands in to irrigated lands. Some soil studies (Table 6) and field experiments were undertaken by the late organism in charge of irrigation (IRYDA) in the Spanish Government after the salt-affection became obvious in several districts. These studies and experiments were discontinued, maybe because in the scenario of an open market, irrigation seems the only way if the agricultural activity is wanted. Now, environmental concerns together with the disputes for water against powerful users and regions could change the social perceptions.
Table 6. Extent of the salt-affected soils in several districts of the Ebro basin after data extracted by Herrero and Aragüés (1988) from several studies of IRYDA.

<table>
<thead>
<tr>
<th>Irrigated district</th>
<th>Year of the study</th>
<th>Surface studied km²</th>
<th>2 &lt; ECₑ &lt; 4 dS/m, and ESP &lt; 15</th>
<th>ECₑ &gt; 4 dS/m, or ESP &gt; 15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>km²</td>
<td>km²</td>
<td>%</td>
</tr>
<tr>
<td>Bardenas</td>
<td>1974</td>
<td>323</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1976</td>
<td>660</td>
<td>128.8</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>567</td>
<td>42.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Cinca</td>
<td>1976</td>
<td>387</td>
<td>26.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Aragón &amp; Cataluña</td>
<td>1981</td>
<td>1359</td>
<td>404.0</td>
<td>29.7</td>
</tr>
<tr>
<td>Flumen</td>
<td>1976</td>
<td>275</td>
<td>28.0</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>359</td>
<td>89.5</td>
<td>24.9</td>
</tr>
<tr>
<td>Monegros I</td>
<td>1975</td>
<td>88</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Monegros II</td>
<td>1979-84</td>
<td>1339</td>
<td>279.8</td>
<td>20.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5357</td>
<td>1001.0</td>
<td>18.7</td>
</tr>
</tbody>
</table>

ECₑ: Electrical conductivity of the soil saturation extract. ESP: Exchangeable sodium percentage.

The perspective of irrigated districts modernization, the Common Agricultural Politics, and the environmental concerns centred in water saving make clear the need of detailed soils knowledge for making decisions. In this way, Nogués et al. (2000) evaluated soils for irrigation systems modernization, taking into account soil salinity and the present market scenario; Nogués (2002) surveyed at 1:25000 scale the soils of an irrigated area, and Nogués and Herrero (2003) assessed the volume of irrigation water saving after modernization. This kind of information, if acquired for broad areas, can help farmers and decision makers to cope with soil salinity.

2. The visited area

From Zaragoza to our first stop at San Simón, we cross first an area on fluvial deposits of gravels, irrigated at less from the Middle Age. The agriculture in these irrigated lands, based in maize and hort crops, is sustainable and very profitable. Now is only threatened by the urban expansion of Zaragoza city. After the village of Villamayor we found the Zaragoza Gypsum Formation, where irrigation was not develop because of the occurrence of karsts. Soils on gyprock have very low water holding capacity, and then yields are poor or nil in dry years (Herrero and Boixadera, 2002). Flat-bottomed valleys are crossed by dry stone walls to retain water from storms and to reduce erosion. Many of these walls have been destroyed to allow the use of powerful machinery. Hills are rounded and covered by sparse shrubs, dominated by Rosmarinus officinalis and Ononis tridentata. We also cross an undulated area on glacis of the Sierra de Alcubierre. The road climbs the Alcubierre Sierra, where over the Zaragoza Gypsum Formation is overlaid by limestone strata of the Alcubierre Formation, topped by lutite and sandstone in the higher peaks of the Sierra. The vegetation is dominated by a tree very common under dry Mediterranean conditions: Pinus halepensis, often bearing the parasitic plant Viscum album.
Stop 1: San Simón
This point, in the border of Zaragoza and Huesca provinces, was much disputed during the Spanish Civil War because of its dominant position on the Ebro valley, including Zaragoza City, and on the pass to the northern area. Southwards we have a look of the arid area with few apparent landscape transformations. Irrigated lands are far, in the terraces of the Ebro and Gállego rivers.

Northwards we see the pre-pyrenean Sierra de Guara, with his highest peak at 2000 m, and the summits of the Central Pyrenees, attaining 3000 m in the France border. The Northern slopes of the Sierra de Alcubierre are more humid and vegetated than the Southern slopes. We also have an overview of our visit area, with the village of Alcubierre, in non-irrigated area. Northwards from of this village, the Canal of Monegros flows from NW to the SE.

Stop 2. Cartuja de las Fuentes
We can see a Carthusian Monastery, founded in 1509 and disentailed about 1835. We climb to a dominant point on the remnants of a glacis from the Sierra de Alcubierre, excavated for the Canal of Monegros. We see the aqueduct of the Canal de Monegros, contrasting on a landscape to the S and SE with sparse vegetation under natural conditions. The tabular relief shows erosion, deposition and incision of ravines (Figure 12).

Figure 12. Two views from the Stop 2 showing the sparse vegetation and the cycles erosion-deposition associated to slopes in a tabular relief. The left photograph shows sprinkler irrigated maize and some paddies in Las Negras depression.

Lands irrigated from the Canal de Monegros can be seen in the Las Negras depression and in the platform Saso de San Juan. Both areas have undergone intensive works to build plots with the adequate size for flood irrigation. Land levelling was slight in the platform, the main works were to put boulders and fragments of petrocalcic horizon out of the cultivated fields. Intensive levelling in the depression was needed to have irrigable fields, but these works destroyed the shallow soils by mixing their horizons with the underlying materials, often saliferous lutite or sodic hojaldre. Soil salinity-sodicity occurs in this depression. The bottom is cultivated only with rice in the years having enough water in the Pyrenean reservoirs, whereas the higher fields in the slopes often produce maize, alfalfa and barley.

We continue travelling on the Saso de San Juan, a platform on a glacis-terrace from the Sierra de Alcubierre. After clearing, dry farming was practised before the irrigation arrival in these platforms. In spite of the residual organic matter, the agricultural results were acceptable only in rainy years due the low water holding capacity of these stony soils. The platforms do not have salinity problems and
are very adequate for irrigated agriculture in spite of the occurrence of calcic and petrocalcic horizons. Now, windbreaks perpendicular to the dominant wind “cierzo”, help to diminish evaporation. Maize is the main crop, with annual yields from 10000 to 13000 kg by hectare. The most common crop rotation is alfalfa standing for five years, followed by wheat. Alfalfa is cut 5 or 6 times by year. The low temperature in spring is a limiting factor. Hort crops like onion, pepper and tomatoes are feasible in these soils, but are not extensively developed due to manpower shortage and to commercialization problems. In the outskirts of San Juan village, some fresh vegetables are produced under plastic or in small glasshouses.

**Stop 3. San Juan de Flumen**

**Stop 3a. The village**

This village, with 229 houses, was built from 1965 to 1969 to establish “colonos”, the new settlers of the irrigated lands. Every family received around 15 ha of irrigated land, a house, tools and animals, financed by a soft loan with fairly small interests, to be repaid in 25 years. All the villages in the new irrigated lands were built in stone and brick, with similar architectonic style, and were encircled by trees. Now many families live in cities, they come to San Juan village in weekends and vacations to be part-time farmers.

**Stop 3b. Las Negras**

The slope shows vegetation maintained by the seepage from the platform. Intercepting trenches were opened to combat the accelerated erosion in the visited slope, with limited success. Piping phenomena are general even in non irrigated plots (Figure 13) leading to the destruction of whole plots. Piping is a big concern for farmers in paddies, where the development of a small tunnel can void the water of one or several paddies in few hours producing heavy economic losses.

![Figure 13. Piping in the surface of an abandoned plot, and its horizontal tunnel discovered by a pedological pit. Piping is very undesirable under irrigation, and specially in paddies.](image)

Maize, alfalfa and barley can be cultivated in the slopes of this depression, but the bottom is occupied by paddies. In this area subsurface plastic pipe drains were installed in many plots to avoid water logging. Now this drainage network is not more needed because the main crop is rice, and pipes are clogged and not functional. The irrigation water shortage of this campaign results in the set aside of many of the lower plots.
**Stop 3c. Erosion of sandstone. Hojaldre buttes.**

Rockfall is frequent in the steep slopes, because of the alternance of lutites with sandstone banks or paleochannels. These slopes are then covered with blocks of sandstone (Figure 14). The seepage associated to irrigation helps to the loss of coherence of the lutite, facilitating rockfall. Less evident in the landscape but very active is the salt weathering acting on sandstone, a process known in the region as “sarna de la piedra” (literally stone-scabies). In fact, very few coarse elements of sandstone are found in soil profiles. Water from irrigation can enhance the salt transport and then the crystal growth in the sandstone surface, producing alveolar forms by salt weathering (Figure 14).

![Figure 14. Sandstone rockfall in the steep area contrasts against the sprinkling agriculture in the gentle footslope (left photo). Salt weathering is important in the destruction of sandstone, producing alveolar forms. Both rockfall and salt weathering can be enhanced by irrigation.](image)

Hojaldre has been dated as Holocene from palinological evidences by Rodríguez-Ochoa et al. (2000). Hojaldre was probably broad spread in the visited area, but now levelling for irrigation and other works have drastically reduced its extent. Small remaining buttes (Figure 15) in abandoned lands allow tracking this material in Monegros and other areas of the Ebro valley. In general these buttes are capped with a contrasting sandy loam horizon densely vegetated with Lygeum spartum, a drought-resistant plant. Several profiles, non perturbated and non irrigated, were studied by Rodríguez-Ochoa et al. (1989).

![Figure 15. Hojaldre has been extensively disturbed and mixed by land levelling works as is the case in the butte of left photo taken near Pallaruelo in 16-9-1979. The capping coarser horizon is covered by Lygeum spartum, with this plant showing slight slant in the direction of dominant wind. The lamination of hojaldre is evident in the right side photo.](image)
Millimetric or centimetric lamination (Figure 16) is the most prominent feature of hojaldre both naked-eye and under the microscope. The overall granulometry of hojaldre is silty-clay or silty-clay loam. The upper sandy loam horizon can be underlain by a natric horizon, with prismatic structure and often with friable nodules of calcium carbonate occurring in groups of vertical disposition (Figure 17). Iron-manganese nodules have been studied by Sanz et al. (1996).

Figure 16. Left photo is a section of 90 cm × 36 cm showing the hojaldre and the overlying horizon. Centimetric lamination of hojaldre is interrupted by old root canals. In the right side photo, a thin section of hojaldre is observed with crossed polarizers under microscope; the layers of clay alternate with layers of silt and fine sand interrupted by two faunal chambers where both materials are mixed.

Figure 17. The natric horizon has prismatic structure and centimetric calcium carbonate nodules. This horizon occurs over the hojaldre, a very distinct material showing centimetric or millimetric lamination.
Stop 4. Sariñena lake
The origin of the lake has been discussed by several authors. Subsidence following deep dissolution processes seems the most accepted hypothesis, even that some authors have invoked aeolian action. The lake is in a platform topped with coarse detritic sediments. Water level raised in past years due to the irrigation in the platform. At same time, pestilence happened after intensive sweene farming. People from the neighbouring village claimed desiccation against the opinion of ecology activists. The rising was stopped by opening an artificial outlet to the neighbouring river Flumen. As a result the water level is now constant, and waters are much less saline than in natural conditions. Sariñena lake is important for several species of birds in their annual migrations between Northern Europe and Africa. The pressure of ornithologists succeeded in to avoid the proposed desiccation of the lake, now under legal protection. A birds’ observatory and interpretation centre was built. Now the number of storks and other birds has increased not only in the lake, but also in all the areas with paddies. Birds, a pest for rice growers, are now considered by many as a support for tourism, an interesting complement to agriculture.

Stop 5. Callén-Almuniente depression
This depression, with an extent of several thousand ha, is excavated in the Miocene alternant lutite and sandstone. The outlet to the river Flumen was impeded by terraces of the river on resistant sandstone, and soil salinity and sodicity were probably common even before the intensive levelling works associated to the arrival of irrigation 60 years ago. To allow the general drainage of the depression, the Flumen terrace and its supporting sandstone, was cut by a trench at the times of the transformation to irrigation. In spite of the drainage works, salinity, sodicity and high pH are found in the soils of this depression (Figure 18).

Figure 18. Plots of SAR (sodium-adsorption ratio) and ECe in samples from several soil profiles of a paddy (plot AC) and of bare land (plot PC) in Callén-Almuniente Depression. Soils with ECe > 4 dS/m are considered saline, and with SAR > 13 are sodic. The median pH at 1:2.4 water to soil ratio were 9.26 for 47 samples of plot AL, and 10.13 for 15 samples of plot PC.
Given the soil salinity and sodicity of many soils, rice is the main crop in this area. Rice cultivation is associated to water table rising in the summer in the several depressions lateral to the river Flumen, and small artesian phenomena can be occasionally observed in some open-channel drainages. After several years of paddle, a continuous layer several decimetres thick is produced. This layer acquires the consistence of adobe, and allows trafficability of paddies with tractors equipped with special wheels. The structural stability of the underlying oversaturated material is very low.

Figure 19. A continuous layer is created by paddling mud and rice straw using tractors equipped with steel cages wheels. The puddle layer is impervious and consistent, allowing trafficability of paddies. The underlying material (hojaldre), often oversaturated in depressions with paddies, is sodic, with very low structural stability.

From Stop 5 we traverse under the Tardienta Aqueduct of the Canal de Monegros to reach the highway Zaragoza-Huesca.
References


ROAD LOG:

Departure from the Conference Hall at 8:30.

0-32 km  Road A-129 to San Simón, in the Sierra de Alcubierre. 10 minutes ascending walk to have a vista of Central Ebro valley, including Zaragoza, and of our visit area.

32-54 km  Road A-1221 and CHE1410. Aqueduct in the Canal de Monegros near to Cartuja de las Fuentes. 5 minutes climb to a panoramic point. Look to non-irrigated and irrigated landscapes.

54- 60 km  Road CHE-1407. Coffee stop at the village of San Juan de Flumen. Contrast between agriculture in non-saline and in saine soils. Piping in agricultural fields. Erosive processes in sandstone. Look at Holocene formations of fine-grained laminated detritic sediments.

60-68 km  Road A-230 and A-1210. Sariñena Lake: from saline to non-saline, from “pestilent water” to “ecological tourism” attractor.

68-97 km  Road A-1210. Lunch at the village of Grañén. Visit to the Callén-Almuniente Depression: saline and saline-sodic soils everywhere. Rice cropping the agricultural solution. Problems with irrigation water shortage in dry years.

97-117 km  Road A-1210 and A-1211. We pass under and on the Canal de Monegros to reach the highway Huesca-Zaragoza.

117-160 km  Road N-330. Highway to Zaragoza.

Expected arrival time to the Conference Hall: 18:30.

100-186 km  Highway A-2 to Zaragoza (about 1 hour).

Expected arrival time to the Conference Hall: 19:00.