Watermills in the historic irrigation system ‘Palmeral de Elche’, Spain: an example of early hydropower exploitation

Ignacio Melendez-Pastor, Jose Navarro Pedreño and Hartmut Wittenberg

ABSTRACT

With more than 180,000 date palms, the Palmeral de Elche is the largest palm grove in Europe. In 2000, United Nations Educational, Scientific and Cultural Organization (UNESCO) declared a part of it a World Heritage Site. Actually, the Palmeral is a historic irrigation system with rows of palm trees flanking rectangular fields and serving as a windbreak and shade for the cultivation of wheat, alfalfa, fruit trees and vegetables. This system and its cultivation methods were mainly developed during the Islamic period and maintained after the Christian Reconquista in 1265 until recently. The main canal Acequia Mayor supplies irrigation water from the Vinalopó River which is then distributed through secondary canals to the different subsystems and fields as well as for domestic purposes. With an average slope of 1:260 (4‰) the main canal has a flow capacity of about 600 L/s. Owing to the topography, the canal must overcome a number of vertical drops where hydraulic energy must be dissipated. Beside the drop structures, at the same time watermills generate water power for flour production. These watermills have been built since the Islamic era and operated until the last century, when they were abandoned or converted for other uses. There are some descriptive publications and documents dealing with the mills, but there has not yet been any attempt to conduct a technical survey and interpretation. This study explores the remains of 11 watermills and determines the dimensions and technical parameters of this hydro-system. The mills were equipped with turbine-type horizontal waterwheels with hydraulic heads between two and more than 15 m. The observations allow conclusions on mill operation, power yield and flour production. A comprehensive description of this early example of waterpower generation in a multipurpose system is undertaken.

Key words | Elche, irrigation, palm grove, Spain, water history, water engineering, watermills, waterpower

INTRODUCTION

The present work focuses on the engineering aspects of an irrigation and watermill system in the historical context of the era. In light of the fast decay of its remains, a survey appeared urgent to preserve knowledge about this achievement of early master builders. A number of key sources are written in Spanish (Castilian) or Valencian, which is the traditional language and co-official with Spanish in the Autonomous Valencian Community. The names of mills, canals, etc. are written here as found in the respective references and locally used.

THE IRRIGATION SYSTEM

The city of Elche (Elx) lies on the lower Vinalopó River in the Province of Alicante, Autonomous Valencian Community, in southeast Spain. Since precipitation, with an annual average of about 300 mm, is scarce and falls mainly during the winter, irrigation was already introduced in the Ibero-Punic era (6th century BC, Gil Olcina 1968). Also under Roman and Visigoth rule, irrigated agriculture was
developed on the banks of the Vinalopó. However, only after the Islamic conquest was the irrigation scheme of Elche given the historic shape and characteristics of the Palmeral. The new settlers from North Africa introduced advanced irrigation techniques based on their experiences for the provision and distribution of water and cultivation in arid lands.

In November 1265 King Jaime (James) I of Aragon took possession of Elche in the course of the Christian Reconquista (reconquest). His vassals and army commanders were rewarded with the already developed areas while the Moors were expelled from the city and resettled on the right (west) bank of the river. Although the ownership structures had changed, the water management system stayed essentially the same. In 1270 the Castilian Infante Don Manuel, Lord of Elche, enacted the rule that the new owners had to operate the irrigation system, ‘as the Moors were wont to do it in their time (…que la ayan así como la salien aver los moros en el so tiempo)’ (Martinez 2004).

A map of the historical irrigation system is shown in Figure 1. Its initial point was the diversion weir Azud (Arabic sad: weir, dam), also called in Valencian Les Taules (The tables, thus a slide gate with wooden panels), the intake structure at the Vinalopó River to divert water into the Acequia Mayor. This main canal runs about 7.4 km along the left (east) bank of the river, practically parallel to it, but with less slope. Secondary canals depart from the main canal at 24 partidores (dividers) for the supply of up to 2,000 ha of land. A further divider diverted a fixed part (2/12) of the total available flow via a siphon to the right (west) bank of the Vinalopó River into the Acequia de Marchena, the main canal for supplying the lands of the resettled Muslim community after the Christian conquest. The sites and names of the 11 watermills are also indicated on the map.

The part of the irrigation area today popularly known as the Palmeral was a zone of intensive agriculture and horticulture divided in huertos. A huerto is a rectangular plot of area typically about 1,000 m². The edges of the fields are shaped as flat dykes (ca. 20 cm high) to prevent the outflow of irrigation water, which is supplied by shallow lateral ditches from the secondary canals. All huerto edges (dykes) were flanked by date palms. The palm trees provided shade, protected against the wind and created the micro-climate that allowed the cultivation of valuable crops and fruit trees. The great trilogy of cereals, olives and vines as the essential legacy of the Muslims was successfully continued under Christian rule (Gil Olcina 1968). Besides their protective effect, the palm trees served further economic and agronomic purposes by producing fruit, wood and fibres.

Irrigation water was supplied according to a strictly timed regulation and proportional to the available water flow (Gil Olcina 1968; Guinot Rodriguez & Selma Castell 2003; Martinez 2004; Gracia Vicente 2006). The flows at any time from the Acequia Mayor were divided into 12 hilos (threads or parts, Valencian: fils). Two parts were constantly diverted into the Acequia de Marchena, the right bank main canal, and one part was reserved for public use. Nine parts remained in the Acequia Mayor for irrigation of the left bank scheme. Water for the different
secondary canals was diverted by lateral movable dividers (partidores) following a detailed allocation policy.

Today, cultivation in most huertos has ceased. Many disappeared due to the expansion of the city or were converted into parks and public or private gardens. The thousands of palm trees, however, which are still there, appear like a green sea and constitute an important tourist attraction. According to a census carried out in 1997 (Ajuntament d’Elx 1998), the remaining historical Palmeral de Elche comprises 177 ha with 102 huertos and 57,000 palms in the city area and 264 ha with 180 huertos and 60,000 palms in the rural areas. In 2000, an area of 144 ha with 82 huertos and thousands of palm trees was inscribed on the UNESCO World Heritage List. An excerpt of a map of the Palmeral de Elche (Gómez Lucas et al. 2009) showing typical arrangements and sizes of huertos can be seen in Figure 2.

THE MAIN CANAL ACEQUIA MAYOR

The Acequia Mayor shows mainly rectangular cross sections. The choice of construction materials depended mainly on the existing subsoil and geological conditions. In rocky terrain, such as in the initial part near the Azud (weir), the canal bed was excavated by chiseling (Figure 3). In other parts, compacted earth is the main material, often reinforced by masonry of natural stones with mortar plaster, to minimize leakage and protect against erosion. Important passages were lined by masonry of shaped stones cut out of rocks. Particularly at the dividers (partidores, diversion inlets to the branch canals), the accuracy and durability of the canal walls were essential for a precise and reliable allocation of irrigation water. The width of the canal varies between 0.90 m in the rocky section and up to 2.40 m at the Partidor de Marchena. The channel depths vary considerably and also depend on the terrain. At the headwaters near the weir, depths of around 1 m with water depths of about 70 cm are found. In sections with dividers and branch canals, depths are lower (50/30 cm) to allow the water supply to reach the irrigation plots.

With a water level of about 118.3 m a.s.l. at the Azud (weir) and 87.8 m a.s.l. at the Ressemblanc mill, the Acequia Mayor has a total drop of 50.5 m over a length of 6,877 m and thus theoretically an average bed slope of 0.0073. This slope, as can be shown by calculations with the Manning’s equation, would yield flow velocities well above 1 m/s. However, high velocities would cause erosion and damage. Higher turbulences could disturb the precise operation of the dividers.

Figure 2 | Excerpt of a map of the Palmeral de Elche showing huertos in their typical sizes and arrangements (Gómez Lucas et al. 2009).
In fact, the Acequia Mayor was composed of nine sections in the form of a cascade. In adapting to the topography, the sections have an average slope of only 0.0034, concentrating the remaining fall height (27 m) at the cascade steps, where the surplus fall energy had to be broken. A conventional technique to do this, as at weirs and spillways, was to build a chute or a drop tower with a dissipation basin. The builders of the Acequia Mayor however were ingenious enough to use at least a part of this energy for driving watermills. A longitudinal section of the upper part of the Acequia Mayor with the sites of watermills falls is shown in Figure 4.

Two of the mills, Moli Nou and Moli del Cèntim, have inflows through mill canals diverted from the Acequia Mayor. The entire flow (two fils, hilos or parts) diverted for the right-bank canal Acequia de Marchena passed through the two Rambla mills. The other mills were built over the Acequia Mayor. Since the canal flow was possibly higher than the mill capacities, all mills were provided with bypasses which were also necessary during standstills.

The divider Partidor de la Marchena played a special role since it supplied the right-bank canal Acequia de Marchena with a fixed portion of two fils (2/12) of the total flow. This discharge was obviously routed completely through the watermill Molino de la Rambla and then through a second mill, before being conducted to the right side of the river via a siphon. Rambla is a Spanish word derived from the Arabic word meaning sandy river bed. Here it implies the Vinalopó River. The mills of La Rambla are different from the other watermills of Elche in their design and hydraulic head, which will be discussed below. Situation, hydraulic heads and other parameters of the watermills are given in Table 1 in the section regarding energy generation.

Although the system has been in operation for more than 1000 years, not much is reported on the flow rates and water volumes in the Acequia Mayor. Water was simply supplied according to the strictly timed regulation and allocation. Gil Olcina (1968) writes that the Vinalopó River can theoretically supply 360 L/s to the irrigation scheme of Elche. He does not mention a source for this value, but it corresponds roughly to the flow available at the Aspe gauging station upstream of Elche in the years 1918–1969 (MAAMA 2012). This flow rate seems low for the historical irrigation scheme. However, it is not likely that water availability stayed the same over centuries, since varying water uses, withdrawals or transfers upstream of Elche, certainly had high impacts on the flow regime. Gil Olcina (1968) reports on page 543 (without further discussion) that one talla, ‘in imitation of the hilo’, represents a flow of 50 L/s. Consequently, 12 tallas or fils probably implied a flow rate of 600 L/s. Current meter measurements by the authors near the Azud (weir) in the rocky section and downstream of the Dos Moles mill in June 2008 yielded flow rates of 528 L/s and 410 L/s with average flow velocities of about 0.7 m/s and 0.8 m/s, respectively. The maximum flow...
capacity calculated with the Manning’s equation based on the flow measurements is slightly above 800 L/s.

In his report ‘Claridad de la acequia de la Villa de Elche’ in the year 1587, the chronicler Baltasar Ortiz de Mendoza wrote (citation in Ajuntament d’Elx 2008): 1 Fil d’aigua = 1 palmo de vara de ancho y el tercio del palmo de altura (one fil of water is equivalent to [a flow] of 0.92 m width and 0.23/3 m depth), thus through a cross section area of about 0.07 m². Consequently, the total design flow of 12 fils would have a cross section of 0.84 m². The multiplication with a typical flow velocity of about 0.7 m/s (see above) yields a design flow of 600 L/s. This result confirms the finding of Gil Olcina (1968). Therefore, it is assumed that a design or standard flow of 600 L/s was diverted from the river into the historical Acequia Mayor. Streamflow in the Vinalopó River is subject to high seasonal variation. Particularly in the drier summer period, the derivation at the weir was often lower than the standard flow, while in wetter periods an intake above 600 L/s was possible.

Of this total flow of 600 L/s or 12 fils (hilos), two fils or 100 L/s, were diverted into the Acequia de Marchena. Ten fils, 500 L/s, remained in the Acequia Mayor, of which one fil was provided for domestic purposes. Three fils, 150 L/s, always arrived at the mill Molino de Ressemblanc (Guinot Rodriguez & Selma Castell 2005) near the end of this main canal. Along the main canal, the available flow decreased as a function of the outflows into the various branch canals. There is no documentation on the flow capacity of the ancient mills of Elche. Values were estimated based on plausibility as discussed below in the paragraph on the individual mills.

### MILL SYSTEM AND TECHNOLOGY

Of 10 of the 11 former watermills, only ruins remain, while the mill house of the Molino del Real has been restored for other uses. The two mills of La Rambla had enough flow capacity to convey the entire flow of two fils to the right-bank main canal Acequia de Marchena. The design flows of the Acequia Mayor were too high to be fully passed through some of the mills situated there. Two of the mills,

<table>
<thead>
<tr>
<th>Mill</th>
<th>Origin</th>
<th>km</th>
<th>Wheels</th>
<th>Head, m</th>
<th>$V$, m/s</th>
<th>$A_s$, m²</th>
<th>$Q$, L/s</th>
<th>$P$, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nou</td>
<td>1423</td>
<td>2.79</td>
<td>2</td>
<td>5.7</td>
<td>9.6</td>
<td>156</td>
<td>300</td>
<td>5.9</td>
</tr>
<tr>
<td>Rambla 1</td>
<td>1317</td>
<td>3.29</td>
<td>1</td>
<td>15.5</td>
<td>15.9</td>
<td>63</td>
<td>100</td>
<td>5.3</td>
</tr>
<tr>
<td>Rambla 2</td>
<td>19th century</td>
<td>3.3</td>
<td>2</td>
<td>5</td>
<td>9.0</td>
<td>55</td>
<td>100</td>
<td>1.7</td>
</tr>
<tr>
<td>Centim</td>
<td>IP</td>
<td>3.38</td>
<td>2</td>
<td>2.84</td>
<td>6.8</td>
<td>110</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>Dos Moles</td>
<td>IP</td>
<td>3.74</td>
<td>2</td>
<td>5.6</td>
<td>9.5</td>
<td>79</td>
<td>150</td>
<td>2.9</td>
</tr>
<tr>
<td>Palmereta</td>
<td>IP</td>
<td>4.12</td>
<td>2</td>
<td>2.28</td>
<td>6.1</td>
<td>123</td>
<td>150</td>
<td>1.2</td>
</tr>
<tr>
<td>Del Real</td>
<td>1306</td>
<td>4.67</td>
<td>1</td>
<td>2.56</td>
<td>6.4</td>
<td>233</td>
<td>150</td>
<td>1.3</td>
</tr>
<tr>
<td>Traspalacio</td>
<td>&lt;1397</td>
<td>4.97</td>
<td>1</td>
<td>2.43</td>
<td>6.3</td>
<td>259</td>
<td>150</td>
<td>1.3</td>
</tr>
<tr>
<td>San Jaume</td>
<td>1376</td>
<td>5.41</td>
<td>1</td>
<td>1.8</td>
<td>5.4</td>
<td>277</td>
<td>150</td>
<td>0.9</td>
</tr>
<tr>
<td>del Retor</td>
<td>1305</td>
<td>5.78</td>
<td>2</td>
<td>1.8</td>
<td>5.4</td>
<td>139</td>
<td>150</td>
<td>0.9</td>
</tr>
<tr>
<td>Ressemblanc</td>
<td>1321</td>
<td>6.88</td>
<td>2</td>
<td>2</td>
<td>5.7</td>
<td>132</td>
<td>150</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 1 | The mills and their main technical values

Figure 5 | Cross section of a typical Spanish watermill of the Elche system.
Moli Nou and Moli del Cèntim, had their inflows by diversion through mill canals. The outflows were fed back to the Acequia. The remaining mills built over the Acequia were provided with bypasses for the surplus water. Bypasses were also needed during standstill periods. Details for every mill are outlined below.

All mills were driven by horizontal waterwheels with vertical shafts. There are two basic types: the open, free jet impulse wheel rodezno and the submerged impeller turbine rodetè. The impulse wheel is especially apt under conditions of scarce flows but higher heads and therefore is common in inland watermills from the Middle East through the whole Mediterranean region to the Canary Islands and overseas (Moog 1994). The submerged impeller, also named regolfo mill (Hawksley 2008), is found where abundant flow compensates for low falls, thus at perennial rivers like the mills at the Río Segura in Murcia Spain, or in tide mills (Wittenberg 2011). Both types are not waterwheels in the proper sense, but rather turbines.

Owing to the limited flows, the mills of Elche were equipped with horizontal free jet wheels (rodeznos). Ample descriptions concerning historical and technical aspects of this mill type are given in the literature (Avitsur 1971; Calvert 1973; Moog 1994). A cross section of a typical Spanish watermill of the Elche system is depicted in Figure 5.

Water is led by a nearly horizontal headrace canal (caz) to a vertical, mostly cylindrical drop tower with a diameter in the range of 1 m. Higher towers often give the impression of a chimney. Avitsur (1971) introduced the name Arubah (Hebrew: chimney) mill for high towered watermills in Israel and Palestine. The tower (cubo) serves as a penstock. From the base of the penstock, a funnelled conduit with a nozzle (saetillo) forms a jet which impinges tangentially onto the blades of the turbine wheel, turning it due to the forces of momentum and diversion. The blades of simple impulse wheels like in the alpine Stockmühlen and in many mills in water-rich mountainous regions in the Himalayas are flat causing considerable energy losses by impact. Scarce flows required higher efficiencies. Thus wheels with concave blades with regularly curved profiles to achieve a deflection of the jet, as described by Leonardo da Vinci as well as in the Spanish books Los Veintiún Libros de los Ingenios y de las Máquinas (Moog 1994), were developed before the 15th century. These wheels are predecessors of the modern Pelton turbine.

Although most of the mills of Elche were still operated during the last century, no single wheel has been preserved or described in detail. In the literature (e.g. Moog 1994) diameters of 0.9–1.6 m are indicated, with 22–45 curved blades fixed in the hub. Headworth (2004) reported that the waterwheels of the Huebro valley mills near Almería had diameters of 1.8 m. However, a drawing in the archive of Elche (Archivo Municipal 1901) depicting a planned modification of the Dos Moles mill shows diameters of about 1.35 m. Because of their lower hydraulic heads, the jet velocities of the mills of Elche were lower than those of the Huebro mills (Equation (1)) and so were the peripheral velocities of the wheels. Smaller wheels yield higher rotational speeds which are favourable for a good grinding performance of the mills. It is therefore assumed that the wheel diameters of the mills of Elche were in the range of 1.35 m.

A timber or later an iron shaft with an iron insert at the lower end rests in a bearing on a wooden beam. One end of this beam (puente) can be lifted or lowered to adjust the clearance between the millstones. The wheel is secured to the shaft by wooden wedges (Calvert 1973). A spindle on top of the vertical shaft was led through the ceiling of the wheel chamber and the bed stone to the runner stone. Except for some smaller parts, such as, e.g. the bearing of the shaft or the spindle, everything was made of wood. Since the runner (upper mill stone) was directly fixed on the wheel shaft, there was no gear or transmission. Consequently, the wheel and the stone had the same rotational frequency. Steel wheels were only introduced at the end of the 19th century.

A free jet wheel which has been restored in a mill on Cyprus is shown in Figure 6. It can be assumed that the wheels of Elche were quite similar. The 32 wooden blades have a double curvature. They are secured by a rim of sheet iron, which surrounds the wheel. Only an orifice in the wall of the wheel chamber (above, left) is where the adjustable nozzle is missing. The plotted rectangle marks a plausible orifice.

The nozzle plays an important role in wheel operation. According to Torricelli’s equation, the jet velocity \( v \) is a function of the hydraulic head \( h \), i.e. the vertical distance from the water level in the tower to the nozzle outlet:

\[
    v = \mu \cdot \sqrt{2g \cdot h}
\]
where $\mu$ is the outflow coefficient, here assumed as $\mu \approx 0.91$ since the nozzle has a favourable funnel shape, and $g$ is the gravity acceleration, $g = 9.81 \text{ m/s}^2$.

In Spain the orifice area $A_s$ is most frequently found in the shape of an upright rectangle (Garrido Aranda 2002; Díaz Rodríguez 2004; Headworth 2004). The ratio of the vertical to the horizontal side varies between 3 and 2. The size of the orifice area $A_s$ is dimensioned for the maximum or design inflow $Q$, thus $A_s = Q/v$. Smaller inflows would mean lower jet velocities and consequently lower hydraulic heads $h$. In this case the water level in the tower would drop. Therefore, the orifice area is adjusted by a little gate or shutter (cerraja) via a handle (llave) from the mill floor. The shutter cannot regulate the flow, as misunderstood in some publications, but adjusts the orifice area in order to maintain the hydraulic head and the jet velocity.

At some sites, the available flows most likely exceeded the mill capacities. Typical impulse or action wheels in drier climatic zones had inflows of only some decalitres per second (such as 20–40 L/s). Higher inflows of around 150 L/s were processed in tide mills (Wittenberg 2011). One limiting factor is the momentum force exerted by the water jet which hits the blades of the wheel on a relatively small area. The momentum force is given by the following equation:

$$F_i = \rho \cdot Q \cdot (v - u)$$

where $\rho$ is the density of water, 1,000 kg/m$^3$, $Q$ is the flow in m$^3$/s, $v$ is the jet velocity in m/s and $u$ is the peripheral velocity of the jet circle of the wheel. Under ideal conditions, the peripheral speed of a water wheel is $u = 0.5 \cdot v$ (as for the Pelton turbine). In reality, due to slippage, it may be only $u = 0.45 \cdot v$. For example, a flow rate of $Q = 0.15 \text{ m}^3/\text{s}$ and a jet velocity of $v = 10 \text{ m/s}$, would yield a momentum force of $F_i = 1,000 \cdot 0.15 \cdot (10 - 4.5) = 825 \text{ N}$, a rather high load to bear for a wooden wheel. For the mill system of Elche a maximum flow of 150 L/s per wheel is assumed.

In the more historically oriented Spanish literature, very little information can be found on mechanical efficiency $\eta$, power and energy generation of horizontal mills, while a wide range of possible values is suggested in some sources with a technical emphasis. The form of the blades has a particular influence on efficiency. Owing to their impact losses, wheels with flat blades like those of the simple alpine Stockmühlen or other traditional mills could attain efficiencies of only 10–15% (Avitsur 1971; Moog 1994). Blades with double curvature however allow a much higher efficiency. Calvert (1973) assumes 43% for the wheel of a Cretan Arubah mill. According to Rühlmann (1875, p. 362), highly elaborated spoon-shaped blades attain efficiencies of 30–35%. Moog (1994) also gives mean values of 30–35% for action wheels and cites values of 29 and 49% for two mills in the Valais. For the assessment of power generation of the historic wooden action wheels (rodezno) of the mills of Elche an efficiency of $\eta = 0.35$ is assumed (Wittenberg 2011). The iron wheels used since the late 19th century probably had efficiencies around 45%. The power $P$ generated by a water-wheel is given by the general waterpower equation:

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot h$$

where efficiency $\eta = 0.35$, water density $\rho = 1,000 \text{ kg/m}^3$, gravitation $g = 9.81 \text{ m/s}^2$, flow $Q$ in m$^3$/s and head $h$ in m. The hydraulic head is the difference between headrace water level and wheel.

The main technical values of the mills at the Acequia Mayor and the Acequia de Marchena (here only the Rambla mills) are listed in Table 1. The mill names are given in abbreviation. ‘Origin’ indicates the time of construction or first documentation, while IP stands for Islamic period. The value km is the canal distance from the diversion weir azud as measured by the authors. The number of wheels and the hydraulic heads are adopted from Archivo
Municipal de Elche (1896) or measured by the authors. Details are explained below in the description of individual mills.

Jet velocities \( v \) are computed by Equation (1). As are the orifice areas necessary for the discharge of the design flows \( Q \), and \( P \) is the power generation at full load (Equation (3)). According to these computations, the maximum power output of the traditional mills with wooden spoon wheels was about 32 kW. The grinding capacity for flour is discussed further below.

DESCRIPTIONS AND OBSERVATIONS ON THE INDIVIDUAL MILLS

In their book, Guinot Rodriguez & Selma Castell (2005) dedicate a chapter to the mills of Elche. It reports on the sites, the date (year) of construction or first mentioning, historical background and development, demolition or disappearance of the mills and other details. Information for the following observations is mainly taken from this source. However, no substantial details about hydraulic and other technical parameters of the various mills are found in this source or in the other related publications. This was one of the motivations for the present study.

MILL MOLINO DE LA RAMBLA

At 3,295 m distance from the Azud, the fixed divider Partidor de Marchena diverts two fils of flow (100 L/s) into the Acequia de Marchena. After about 80 m of length in western direction, the Acequia becomes the headrace canal (caz) of the first Rambla mill and arrives at the penstock tower (cubo) on the steep bank of the Vinalopó River. The height of more than 15 m and its architecture makes this Arubah mill unique among the mills of Elche. It is reminiscent of the mills of the Eastern Mediterranean that were built particularly under Venetian rule.

The Molino de la Rambla was built in 1318 as a component of the river crossing system of the right-bank main canal. The entire flow of two fils (100 L/s) was routed over one wheel and left the mill through the tailrace about 16 m below. There it became the inflow to the cubo of a second mill, probably added in the 19th century to exploit the hydraulic head of about 5 m with two wheels. The tailrace of this second mill was connected to the Raifa, the syphon crossing the river. Today the impressive Arubah tower is still standing and the upper rim of the second cubo, though filled with rubble, is easy to find. The foundations and rear walls of the mill houses and the remains of the tailraces were used to estimate the dimensions of the scheme. The location map (ground plan) and longitudinal section of the former Rambla mill cascade based on the surveying and field investigations which were performed by the authors are depicted in Figure 7. The present-day remains of the Rambla mills are shown in Figure 8. The contours of the former mill houses, wheels, tailraces and the cubo of the lower mill are outlined. This exceptional system really deserves better protection and conservation.

MILL MOLINO DE LA TORRETA O DEL CÈNTIM

The remains of this mill are found less than 100 m downstream of the divider of the Marchena canal 3.38 km from the Azud. Only little information is available and there is no information about when it was founded. Guinot Rodriguez & Selma Castell
(2003) date its origin in the late Middle Ages ‘without it being illogical to consider an Islamic origin’.

The name Torreta was used because a little tower is erected at the mill house. The headrace of the mill branches from the Acequia Mayor and bifurcates a short distance later to feed the two cubos, each with 1.50 m inner diameters. These sizes and the widths of the headraces suggest that both wheels were supplied with a maximum inflow of 150 L/s. The tailrace canal today is hardly traceable. It reached the Acequia Mayor upstream of the next mill (see Figure 4).

MILL MOLINO DE LES DOS MOLES O FÁBRICA DE FERRÁNDEZ

The name refers to the two wheels (dos moles) of this former mill and the factory erected at the site in 1880. The mill was located 3.74 km from the Azud. As with the mill Torreta, there is not any information on the time of its origin, except that it was operated as a flour mill since the Middle Ages, possibly from the Moorish time, until the late 19th century.

The mill or its remains are no longer accessible since they are covered by the buildings of an abandoned factory. A drawing in the archive of Elche (Archivo Municipal 1901) depicting a planned modification of the Dos Moles mill reveals however, that the mill had a cylindrical cubo of 1.8 m diameter and 5.8 m hydraulic head above the two nozzles. It is assumed that each wheel had a flow capacity of 150 L/s. A bypass conducted the surplus from the headrace to the tailrace.

MILL MOLINO DE LA PALMERETA

The existence of this mill at 4.12 km has already been documented in the late Middle Ages. Under the popular name Palmereta (little palm tree), it was first cited in 1769 in the acts of the municipality of Elche. Guinot Rodríguez & Selma Castell (2003) suggest that its origin may have been in the Islamic era. The mill was equipped with two wheels. Because of the modest hydraulic head, it is assumed that only 200 L/s were passed through the wheels, while the exceeding flow was led through a bypass.

In 1886 a textile factory was built at the site which used the drop to generate water power. Today, both the mill and the factory are as good as gone. What remains is possibly what was the entrance to the cubo. The Acequia vanishes underground.
MILL MOLINO DEL REAL

This mill is situated at the Acequia Mayor 4.67 km from the Azud in the present-day Municipal Park. The name El Real is believed to be derived from the Arabic al-riyad (garden). In 1306 King Jaime II of Aragon authorized the reconstruction of a mill at this place, so 'as it worked in the time of the Moors' (Ajuntament d’Elx 2012). Hence, the Molino del Real is possibly the successor of an older Moorish mill. It worked as a flour mill until the 1940s and was then used as a store for gardening tools. Around 1980 the mill house was rebuilt for other purposes. The technical equipment, such as wheels, millstones, etc., was removed without documentation.

Being one of the oldest mills, the Molino del Real is also the most popular in the city due to its location and the imposing river-side facade. A view of the complex from the south in a photo from around 1940 is shown in Figure 9. The 12 arcs built above a retaining wall on the steep bank of the Vinalopó River (partly seen in the right half of the photo) are the most impressive structural elements. However, they are only part of the annexes and not part of the millhouse itself, which is the rectangular building in the center.

The Acequia Mayor (water surface colored blue in the photo) approaches from the north (left in the photo) and reaches the penstock (cubo) with its circular shape in front of the millhouse. A photograph of the former wheel chamber made in 1970 shown in Ajuntament d’Elx (2012, p. 17), suggests that the cubo had two nozzles and hence two wheels. The tailrace was perpendicular to the headrace canal leading the outflow to the left to the downstream Acequia Mayor (blue, above in Figure 9). For flows exceeding the mill capacity, there was a lateral overflow on the left side of the headrace canal. Most of the time there was enough flow at this part of the Acequia Mayor to supply both wheels with 150 L/s.

MILL MOLINO DE TRASPALACIO OR EL MOLINET

At this site, 4.97 km from the Azud, the Acequia Mayor reached the walls of the old city of Elche and was led through the back wall of the Altamira palace (behind the palace – tras el palacio). The mill was the last building just outside the gate, therefore also named Molino del Portal and it was a small mill, El Molinet, equipped with one wheel. Cited first in 1397, it worked as a flour mill until the 1940s. Today the mill has completely disappeared. The former opening in the wall for the Acequia Mayor has been closed with masonry but is still easy to spot.

MILLS MOLINO DE SANT JAUME AND MOLINO DEL RETOR

Both mills were located within the walls of the old city. The Sant Jaume mill, first cited in 1376, was equipped with one wheel and the Retor mill, probably built in 1305 with two wheels. Both were operated until the early 20th century and later demolished without leaving any visible traces.

MILL MOLINO DE RESSEMBLANC

This is the last of the historical mills at 6.88 km of the Acequia Mayor. The oldest source dates back to 1321 when King Jaime II ordered an investigation of the opportunity to reopen a mill in the fields at Rabat Sambach. Rabat is Arabic for fortress and probably refers to the tower Torre de Ressemblanc near the mill. So the construction of the mill may have taken place in the Islamic era.

The flow at this point of the main canal always had to be three filis, hence the design flow was 150 L/s. As at the Molino del Real, the Acequia Mayor arrived here at the penstock (cubo) of the mill from which the water was
discharged on two wheels. A view into the cubo and the two outflow hoppers leading to the nozzles for the water jets on the wheels is given in Figure 10.

According to Guinot Rodriguez & Selma Castell (2003), normally one of the two wheels and grinders worked while the other was on stand-by. Flour milling continued until the 1950s. After more than 600 years of operation, only recently the whole mill except the cubo has been demolished.

ENERGY GENERATION AND MILLING CAPACITY

As shown in Table 1, the maximum power output of the traditional mills with wooden wheels and double-curved spoon blades was about 32 kW. Later, from the 19th century, when iron wheels were used, higher efficiency may have allowed a power yield of over 40 kW.

The specific energy consumption of mills depends to a large extent on the required fineness of the flour. Today, flours in the fineness ranges \(d_{97} = 144 \mu m\) and \(154 \mu m\) can be produced with an energy rate of 32 kWh/t and 15.4 kWh/t, respectively (Degant 1999, p. 618). According to Jespersen (in Moog 1994, p. 45), the grinding of wheat of the fineness of \(d_{97} = 144 \mu m\) requires a mean energy rate of 74 J/g, corresponding to 20.6 kWh/t. It can be concluded that an energy consumption of 20 kWh/t was typical for horizontal mills with larger deviations, depending on the grinding material and the grinding intensity (Wittenberg 2011). Under this assumption, the Rambla 1 mill, for example, could grind one ton of wheat in about four hours. The entire system under full charge had a grinding capacity of about 7.5 t/h, corresponding roughly to 10 t of bread.

CONCLUSIONS

The watermills at the main canal Acequia Mayor of the historic irrigation system of Elche fulfilled two tasks. They served as drop structures where hydraulic energy was dissipated so that the canal slopes were moderate and the flows subcritical. The watermills mainly generated power for flour production for daily bread. An analysis of the remains of the mill system makes it possible to describe the technical aspects and to quantify the potential of energy and flour production in the Middle Ages. Despite limited theoretical understanding and technical means, the old master builders apparently followed the same basic logic and thinking as today’s hydraulic engineers. This is the only report on the technical and operational aspects of the watermill system of Elche. It is intended as a base for understanding, further research or restoration.

ACKNOWLEDGEMENTS

Valuable information was obtained from the Comunidad de Propietarios de la Acequia Mayor del Pantano de Elche (Community of Owners of the Acequia Mayor) and from the Archivo Municipal. The DWhG Deutsche Wasserhistorische Gesellschaft (German Water-historic Society) granted a travel allowance for the third author. Authors are indebted to Paul Lauer, M.A., University of Lüneburg, for the proof-reading of the English text.
REFERENCES

Ajuntament d’Elx 2012 Proyecto de rehabilitación y puesta en valor del “Molino del Real”.
Archivo Municipal de Elche 1896 Sig.63/50, Plano de niveles de la Acequia Mayor de Elche, de la pared del pantano al molino de Palacio (Cayetano Martínez and José Picó).
Archivo Municipal de Elche 1901 Sig. 46/10, Proyecto de la Sociedad Ferrandez y Cía.

First received 10 March 2015; accepted in revised form 13 May 2015. Available online 8 June 2015