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# Hydraulic Anatomy of Guadiana Springs. Part II. Hydropower Genesis

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## Abstract

Guadiana Springs are an exceptional landmark where the surplus water of the largest Spanish aquifer used to emerge, setting an oasis that powered up to sixteen watermills located along forty kilometres of the river's upper reach. Such industrial hub lasted until the second half of the last century, when drainage works, and aquifer overdraft brought along a distressing scorched land where water had been dominant for centuries. As this unique heritage is about to fade away without knowing its genesis, this independent PhD research attempts to shed light on its likely origins, by assessing the most probable driving forces that promoted its uprising under different standpoints. The logical methodology commences by outlining the study case on the earliest known historic and archaeological references, follows an historiographical assessment on those key factors influencing the expansion of hydraulic works, inferring a bidimensional technological diffusion pattern experimented over the Mediterranean and Middle East regions. It focuses on irrigation and hydropower riverside assets, to compile real examples of Iberian riverine hydraulic works referenced during the thrilling Andalusian period. To conclude, a relationship between work typology and likely construction period is established, distinguishing those watermills that would have disrupted the due operation of the system.

**Keywords:** Watermill genesis; Hydropower diffusion; Geo-historiography; Andalusian heritage

## 1. INTRODUCTION

The Guadiana River used to spring in an arid plain, arranging a meandering marshy landscape without fluvial terraces (Hernández-Pacheco, 1955). Such natural singularity was granted by the freshwater stream that emerged from the underneath, but currently overdraft, Aquifer 23 (BOP Ciudad Real, 1987). This oasis has been inhabited at least since the 30th century BC during the Bronze Age (Urbina & Urquijo, 2017).

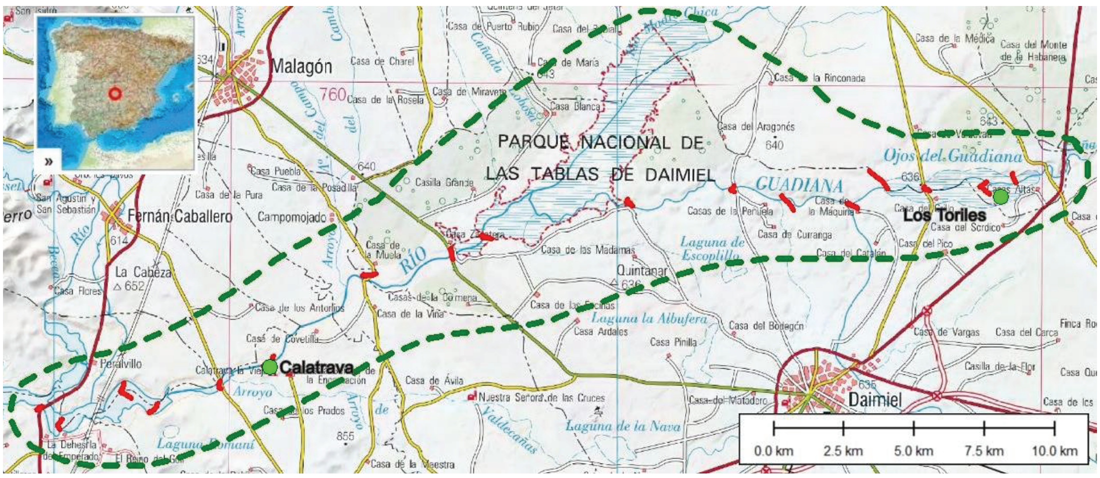

**Figure 1.** Study area location on National topographic map 1:200.000 (IGN ©, 2008)

Vestiges of small dams still endure, which's primary function was to provide the necessary hydraulic head and flow to power the associated watermills but also, created environmental-rich water bodies and allowed pass over the marshy riverbed. These are scattered along forty kilometres, from the upper springs (ETRS89; UTM-H30 [m]: X= 455.792; Y=4.332.885) down to the actual Vicario reservoir tailwater (X= 419.707; Y=4.323.796m), setting the river reach under study and where also, two ancient human settlements outstand: Los Toriles (X= 453.038; Y=4.331.473); and Calatrava (X= 427.750; Y=4.325.383m) (Figure 1).

 

The genesis of this hydraulic asset is uncertain, as just few weirs or watermills are succinctly cited between the 10th and 13th c., and the earliest detailed system description came by the late 16th c. through King Felipe II's Topographical Report (Campos & Sevilla, 2009). Then, the aim is to propose a reliable hypothesis on its origins, considering that it was mostly built prior to the Christian domination of Al-Andalus. The methodological approach considers two main pillars: the history of civilized mankind that matches with the engineering one, as humans are a mere tool-using animals (Fleming & Brocklehurst, 1925) and the concept of "World system analysis" (Wallerstein, 2004), which assesses ancient social interactions with scarce written references and within homogeneous regions.

Thus, the time of interest starts with ancient-known civilizations capable of developing civil works, moving onto the Hellenistic and Roman periods when hydraulics was theoretically available and there were continuous interexchange fluxes that occurred with Iberia (Dangler, 2017). Subsequent Arab uprising and rapid domination of these regions of Europe combined inherited knowledge to spread out innovative and cost-effective engineering solutions, especially during their eight-century presence in south-western Europe.

The subsequent analysed spatial limits are the Mediterranean and Middle East boundaries, considered during the time period under scrutiny as an area of "mutual intelligibility" wherein shared languages, values and conceptual repertoires lubricated the cultural communication and made it possible for multi-ethnic and multi-confessional societies to find a common ground and function together (Catlos & Novikoff, 2018).

Once the target, time and space were defined, the next point was to assume that the hydraulic machinery was limited to vertical waterwheels and helix turbines, disregarding the norse type for intrinsic environmental limitations of hydraulic head. Then, the geo-historiographic approach was undertaken, drafting a diffusion pattern of both technological origins and probable engineering trends that brought about the implementation of riverine hydraulic works over the Mediterranean and Middle East regions.

Finally, it was linked in the discussion chapter to a physical and hydrodynamic system characterization (Doncel Fuentes & Florín Beltrán, 2020) and concluded with a proposal of the relationship between weir typology and likely construction date.

## 2. HISTORIC BACKGROUND

La Mancha hydraulic infrastructure during Bronze period is marked by a singular type of construction known as motilla. It is basically a fortified round-shaped settlement made of limestones and clayish mud, with a viewing tower and a water-well in its core. It is considered the oldest hydraulic infrastructure of Iberia, there are just thirty-two units over Guadiana River upper basin and no similar references can be found elsewhere (Mejías, Benítez, López, & Esteban, 2015).

Later settlements were located on promontories, known as oppidum, essentially real state-cities housing independent political and administrative hubs, relatively populous and equipped with the necessary living facilities (Lorrío, 2012). Both settlements under scrutiny, Los Toriles and Calatrava La Vieja can match to this typology and origin (García Huerta & Morales Hervás, 2010).

### 2.1 Ancient settlements

Los Toriles lays on a natural peninsula of ten hectares, located two kilometres downstream the Springs. It was populated at least for ten hundred years, having unveiled ceramic fragments from the Iron Age and a necropolis in use since the 4th c. BC until the 3rd c. AD (Urbina & Urquijo, 2017). This place was also cited as Iâna by the 12th c., apprising the singularity of the Guadiana Springs (Al-Idrīsī & Abid Mizal, 1989).

About thirty kilometres downstream is found the second site of interest, Calatrava La Vieja, it was re-founded by 785 AD to control the region between Cordoba and Toledo, and fortified five decades later by the Umayyad Emir Abdurrahman II (Lèvi-Provençal, 1957). The definite pacification of Al-Andalus was brought by the later Caliph Abdurrahman III in early 10th c., commencing then the most propitious epoch of the Iberian Middle Age (Dozy, 1920). However, upon Caliphate decomposition followed an unrest period of devastation, leaving the countryside practically uninhabited as people sheltered into fortified places (Torres Balbás, 1957).

During the Caliphate, the citadel facilities were appraised as the lodging services, markets, baths and shops, which were duly protected by a one and a half kilometre-long massive stone wall, crowned with forty-four towers and a defensive wet-perimeter moat (Hawqal, 1971). The place fulfilled the conditions for a long-lasting Andalusian city: nearby profitable agrarian land, pasture, and woods to obtain resources and finally, the most precious God's gift, water at hand (Jaldun, 1377).

Geographically, it lays on a five Hectares plateau elevated up to forty meters from the marshy Guadiana riverbed, about thirty kilometres downstream from the Springs. The River could be crossed thanks to a 630 m-long winged weir that fed the Alzapierna watermill, which was located on the left margin at 400 m downstream of the North-western citadel's edge (Figure 2). This weir was cited in 977 AD, when the young Almanzor, acting as Minister of War, considered cutting the weir (sudd) to prevent Christian's raids into the citadel (Lèvi-Provençal, 1957).

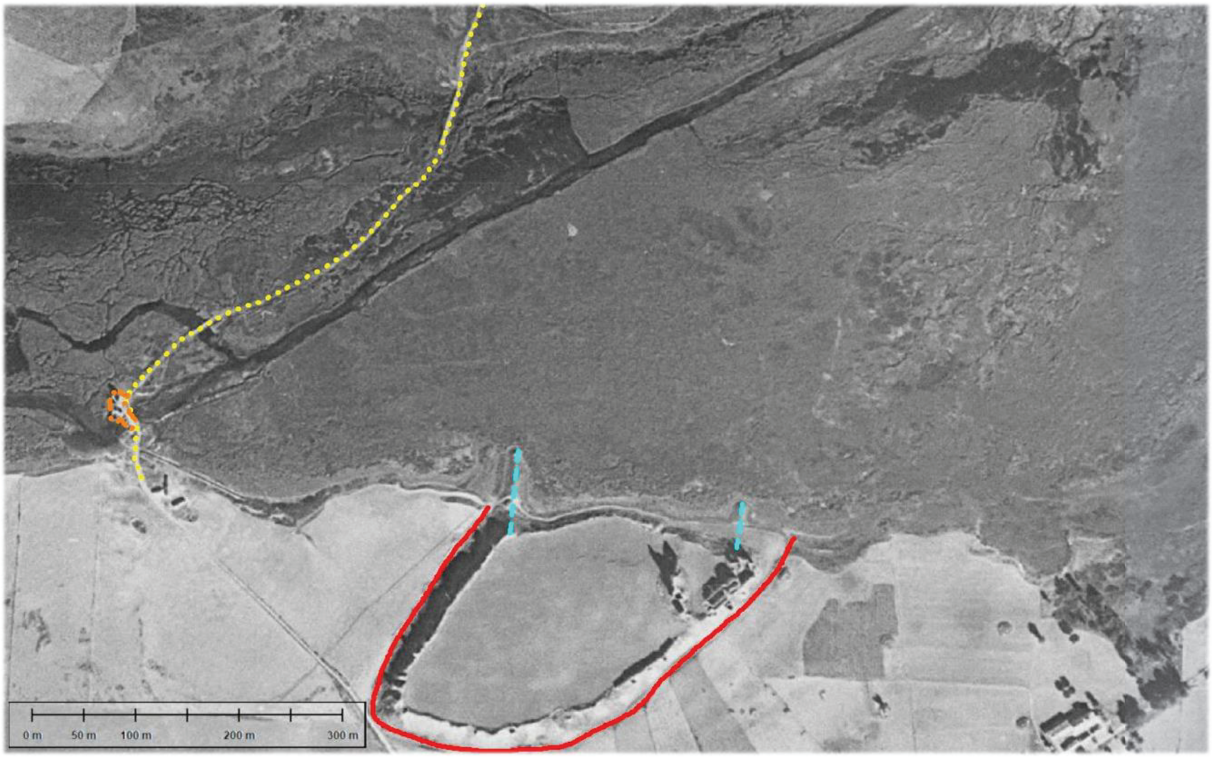


**Figure 2.** Calatrava hydraulic complex: weir and watermill (dotted-yellow), corachas (dashed-cyan) and wet moat (solid-red) on (CEGET, 1956-1957)

Moreover, there are remains of at least two outstanding water intake works known as corachas: a massive wall laid into the riverbed with a stream vertical waterwheel on the edge, pouring the flow into its crest canal and conducting water within the walls, where another wheel, most probably a treading type elevated the water into the city's cistern (Martínez Lillo, 1994).

### 2.2 Watermills

The following reference to Alzapierna asset took place in 1147, after King Alfonso VII conquered Calatrava. He granted to the Segovia's archbishopric the land and properties of the former city's governors, which included vineyards, gardens, country houses, fisheries, and watermills (Torres Balbás, 1957). These productive assets were highly treasured by the Christian warlords, eager to control these income generators as a Royal payback for their holy war services.

In 1150, the Griñón watermill would have been included in the Consuegra Castle donation to Mr. Rodrigo Rodríguez (Hervás, 2011). Since then, few references on disputes of watermill's ownership and operation interferences can be found, but the most important literary reference is the detailed description made of the country, ordered by King Felipe II by the late 16$^{th}$ c., addressing a specific chapter for milling and relevant hydraulic infrastructure (Campos & Sevilla, 2009).

The owners or construction dates are informed, and even the watermill typology is distinguished: aceña (vertical waterwheel [WW]), rodezno (milling stone [MS]) and batán (fulling mill [FM], equipped with vertical waterwheels). This historic characterization data is summarized by hydraulic assets (**Table 1**), having including further references: (*) stands for (Melero Cabañas, 2014) and (**) for (Celis Pozuelo, Mediavilla López, Santisteban Navarro, & Castaño Castaño, 2019).

## 3. HYDROPOWER DIFFUSION

Globally, the earliest hydraulic works were implemented by Sumerians or Pharaohs to reclaim and control potential flooding areas by canals, embankments, and dams. Whereas the irrigation use of the latter would have occurred by the 20$^{th}$ c. BC over the Mediterranean and Middle East regions, contemporary to the implementation of las Motillas. Nonetheless, the earliest reference of any water-driven irrigation machinery is dated by the 6th c. BC (Ewband, 1856), long after the required ancillary civil works know-how was available.

 

### 3.1 Classical antiquity

The hydropower's theoretical introduction was in Alexandria by the 3rd c. BC, where Archimedes and his fellow scholars developed the necessary scientific foundations, but this incipient technology was barely implemented for centuries. Roman hydraulic works focused on satisfying urban needs, quality predominated regardless of the canalization cost, locating the intake at river's upper reaches or natural springs, often catalyzed by qanats. This fact, together with the fluvial transportation preference and the dreaded devastating flooding events, prevented them from building any dam on lower river reaches (Nadal, 1980).

The common Roman dam presented a straight crest alignment resembling a thick wall, capable of storing up to a few million cubic meters, with no fixed spillway implemented as overtopping was a rare event within such limited catchment areas. Later, this typology evolved into triangular cross sections with lower height, following Oriental trends (Castillo, 2007), presenting curved plans with larger spillway capacity, suitable of colonizing lower river reaches.

However, hydropower was rarely implemented as the society had alternative and cheaper energy sources. This situation shifted upon the Empire's twilight and especially in the Oriental part, when slavery's prohibition brought to light a labour shortage in the incipient industrial revolution. But its effective diffusion was negatively influenced by social and political conditions of unrest. Then, despite of mastering hydraulic works, Roman hydropower diffusion can be regarded as incomplete and mostly limited to adaptations of existing water systems or bridges (Reynolds, 2002). Under Byzantine Emperor Justinian, most of Roman hydraulic know-how and regulations were compiled in the research Corpus Iuris Civilis, published in 550 but with no explicit mention of watermills.

Downscaling to Iberia, Hispania had been one of the most prosperous provinces of the Roman Empire, where numerous hydraulic systems were constructed to satisfy urban and irrigation needs. Near the study area outstands Toletum or Consaburum schemes, equipped with the typical slender dams and long canalizations, but with scarce watermill examples.

### 3.2 Early Middle Ages

Later Barbarian invasions over Iberia caused unrest until the late 6th c. when the Visigoth realm defeated their fellows. Then, Recopolis city was erected and equipped with a typical Roman water supply system, without any trace of work on the nearby Tajo River. That simultaneous Byzantine occupation of Southern Iberia could have introduced certain riverine hydraulic works for irrigation, using the undershot vertical waterwheel and curved weirs by riversides. Although no evidence can be traced, hydropower began to develop over most Rivers, as pointed out by an early 7th c. report (Sevilla, c. 636), as well as the legal framework that explicitly defended watermills (Scott, 1910).

Islamic uprising and expansion over the Oriental and Mediterranean regions resuscitated the classical scientific and philosophical knowledge, compiling and observing physical evidence to design fresh engineering solutions in arid regions. The Omayyad and later Abbasid dynasties followed Persian and Byzantine administrative structure, observing Quran mandates on water management with a secular background. It is important to highlight that water was not considered private, just a gift of God but managed by the Caliph, prioritizing its use for human consume, irrigation, timber transportation and industry.

This approach resulted in an integral and effective use of water resources, developing uncountable works across the length and breadth of their domains, becoming the fathers of mainstream hydraulics (Díaz-Marta Pinilla, 1987). Multipurpose small dams and associated hydraulic machinery were implemented in most Rivers under their influence, reaching the apex by the 10th c. during the so-called Islamic Golden Age.

Arabs and Berbers hordes took most of Iberia in just two years, but internal divergencies would have not favored stable, social, and economic conditions to crystalize massive civil works. This situation changed upon the arrival of Abdurrahman I and specially by the early 10th c. with the Caliphate, establishing a centralized state, easing a wealthy interethnic cooperation, boosting scientific research and earthy applications. Besides, an efficient taxation system was established, inducing productivity through mechanization, and even forming a certain state of monopoly on grain production.

Inherited water infrastructure was rehabilitated and enlarged by applying hydraulic works and machinery on private housing, farming and industrial uses (Forbes, 1993). Then, based on conserved references since the 8th c., hydropower was intensively developed over any suitable stream to complete the first industrial revolution of Iberia, induced by both public and private interests (Camarero Castellano, 2011). The constructors were multidisciplinary empiric artisans, carpenters, and builders, who improved water technology and engineering methods (García Tapia, 1989).

Therefore, it can be inferred that hydropower was implemented along existing canals during the late-Roman period, but the difficulties to control the countryside where this hydraulic infrastructure lays, induced the implementation of riverine works within or near fortified citadels. This adaptation to changing conditions was undertaken by indigenous communities and influenced by novel Eastern technological practices, being the definite push given under these favourable conditions that occurred during the Caliphate. Despite of the unrestful conditions during the subsequent petty states, such administrative decentralization did promote scientific research and even contributed to erect civil works, as every Taifa king would dare to imitate the previous splendour and magnanimity.

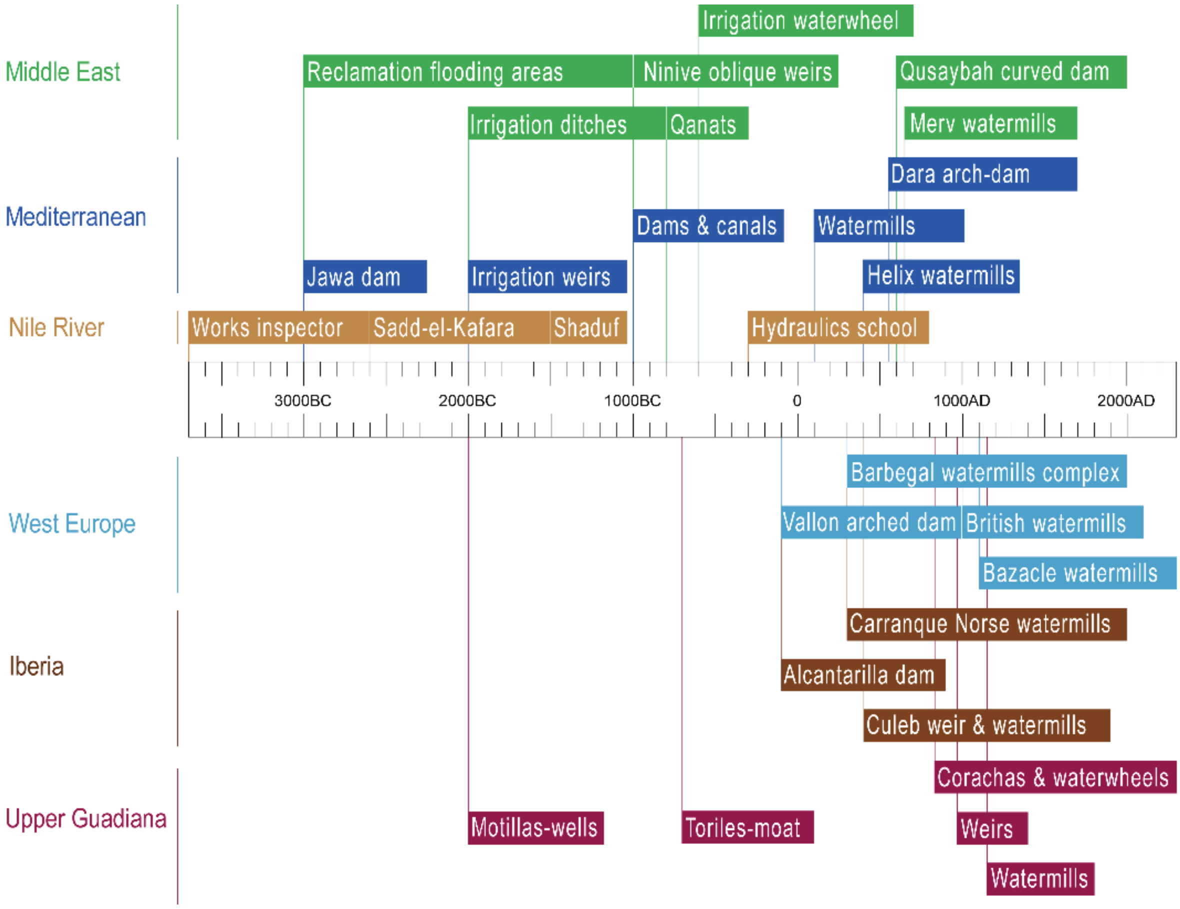


**Figure 3.** Hydraulic technology bidimensional diffusion evidences

Figure 3 compiles the most outstanding references and achievements on hydraulic works and machinery. These are outlined by geographic and time horizons in the vertical and horizontal axes, respectively. By the 20$^{th}$ c. BC early irrigation dams were undertaken contemporarily to the Motillas, meanwhile hydro machinery would have appeared by the 6th c. BC, although the scientific foundations must have occurred three centuries later. Watermills references can be traced since the late Roman period, intensifying during its twilight to bloom in the Middle Age.

## 4. IBERIAN RIVERINE WORKS

Firstly, the typical riverine weir layout is markedly oblique with a certain bending, even winged convex to the flow’s direction, pointing out that crossing was not its primary function. This plan increases the spillway capacity to direct the flow towards the intake by outlining a funnel shape with minimum energy loss. It is just a few meters-high with scalene triangular cross section, to gently alleviate extreme events and to minimize the foot-scouring, laying on a wooden-steak embedded foundation of stones and mortar.

These riverine weirs powered hydro machinery demanding large flows and low heads, as the undershot vertical waterwheel or the helix waterwheel. The first type was the earliest and mainstream implemented, especially for irrigation, but if more output power was required to run industrial appliances, the efficient and reliable helix waterwheel was also an option. Such upgrading required little investment, as weir, outlets and foundations were used as disposed, being just necessary to erect the cylindrical cube and the basic structure to set the upper milling room.

The Duero River basin has presented continental climate and semi-arid conditions alleviated by aquifers, with a prominent cereal production, therefore most vertical waterwheels were used for grinding grain. By the early 10th c. numerous units were described in this region recently taken by the Christians, after decades deserted, such as the Olivares set erected in Zamora by exiled Mozarabs who probably imported it from their homeland (Martínez Díez, 2011).

The Ebro River's middle reach shows a meandering morphology proper for orchards, where waterwheels up to a dozen meters-diameter were primarily used for rising water. Outstands the Tudela case (Al-Razi, c1650), founded by the 9th c. and became an important Jewish hub. A cascade set of hydraulic assets with oblique weirs remains fifty kilometres downstream Zaragoza, used for both irrigation and milling, and are properly referenced since 12th c. (Bolea & Puyol, 2011); (Laliena, 2008).

Similarly, the hydro works located along the Tajo River would have been used for both irrigation and grinding. Outstands the Buenamesón inverted winged weir, the Aceca oblique one or the cascade set by the city of Toledo, all referenced before the 12th c. and still upright. Within this regard, Diaz Marta affirmed that Toledo riverine assets were constructed during the Andalusian period with a simple typology, iconic environment adaptation and usefulness that has been reproduced during centuries.

In the Guadiana River basin, the cascade set of Norse watermills deserves attention, located at Rio Frío Creek near Almaden, also allocated to the Calatrava Order by the 12th c. Downstream riverine weirs existed until reaching the Ocean, but most are flooded by large reservoirs, and those visible ones in Badajoz or Mértola cannot be adequately dated.

Eastwards, the ancient Roman Valencian orchard was expanded since the 8th c. throughout up to nine diversion weirs, reaching its apex during the Caliphate, when the current management body was established. Alongside, the Segura River from which the Contraparada weir fed since the 11th c., at least, up to thirty thousand hectares of thriving orchards through two different canals at both margins. Its tributary Guadalentin, watered different plots depending on the season through a novel system of gates and canals, mostly allocated to the Calatrava Order by 1252 together with the watermills by the city of Alcantarilla.

The common watermill typology over the Iberian Levant was the vertical waterwheels, known as Ñoras, mostly installed within the canals and used for pumping as well. By reason of the broad-minded attitude of Aragon's Kings, such as Jaume I, a relevant part of this heritage has been conserved and still is in operation.

Regarding the great Andalusian River, outstands the Cordoba milling house cited by the mid-8th c., which would match to the Culeb asset, located downstream from the Roman Bridge. It was later reported with three Aceñas and a magnificent waterwheel, work that was purchased by Al-Hakam I and even attracted the scientific interest of the Caliph Al-Hakam II. Upstream, the Martos unit can be found, equipped with four vertical waterwheels, and later rehabilitated with helix turbines. Whereas downstream still endures a curved weir with two watermills at both margins, firstly referenced by the 12th c., and no further units can be traced reaching Seville and the Ocean, except for tributaries such as Guadaira River.

The first Culeb asset reference dates just from thirty years after the Arab occupation, therefore it would point out that it was built during the previous Byzantine presence by the late 6th c. Thus, this dating would agree to San Isidoro's assertion of presence of vertical waterwheels in Iberia, meaning the incipient development of riverine hydropower in Iberia. Anyhow, the acquisition in the early 9th c. by the Emir confirms that this sector was strategic for the State, and then, it had to be progressively promoted all over the realm extent.

## 5. SYSTEM'S GENESIS

The upper reach of the study area is marked by Los Toriles or Murum site, the regional city of reference until the 3rd c. AD, when the necropolis would have been abandoned. This fact would infer a dramatic depopulation of the area because of the increasing unrest conditions of the Empire's twilight, which may have lasted until the early 8th c. as no literary or archaeological reference can be traced.

Apparently, the nearest Arquel weir could be associated to this settlement during the Roman period, but this assumption has been disregarded due to the following reasons:

- core materials and plan typology do not match to the common Roman design
- crest longitude and winged plan points a clearly hydraulic primary design
- the site's moat would have been ineffective, as the weir connected both margins
- terra sigillata was found in its core, inferring its post-roman construction
- the weir would have blocked the fluvial transport

The rest of assets share the first point, which summed to the pathway's assessment, the absence of any archaeological record and the regional hydropower diffusion dynamics, leaves little chance for any late-Roman or Visigoth origin. The subsequent period pivots around the establishment of the city of Calatrava by the late 8th c. and particularly since 853. This work had to be erected during the city's foundation, essential to cross the Guadiana River and hydraulically, to provide a minimum water depth for the corachas's proper operation and the industrial use to satisfy the city's milling grain needs.

Prior to approaching the intrinsic system's genesis hypothesis, this has to consider that the essential structure of any hydraulic system has been conceived and projected from the beginning (Barceló, 1989); the development of civilizations in arid regions is only possible through dictatorial regimes able to invest considerable amounts of resources on hydraulic works (Wittfogel, 1957), also known as “oriental despotism” (Roldán Cañas, 2007); and the inherent strong relation between the execution of largescale public works and a solid and stable government operating under peaceful periods (Smith, 1976). Undertaking such magnitude of works, about a quarter of a million of cubic meters for earth embankments apart from the milling houses and masonry vents, required a vast taskforce, few decades of construction and a firm promoting agent. Grain milling was a strategic sector that even was monitored by the Caliph, pointing out that most of the system had to be erected by the 10$^{th}$ c.

In any case, every asset was tightly interconnected as the hydraulic operation mode did affect the rest of units. The system was drafted according to two basic parameters: hydraulic head at least of one meter to run vertical waterwheels or two meters for helix turbines, with minimum weir length focusing on cost-effectiveness but also in hydraulic efficiency, demonstrated by the winged layout.

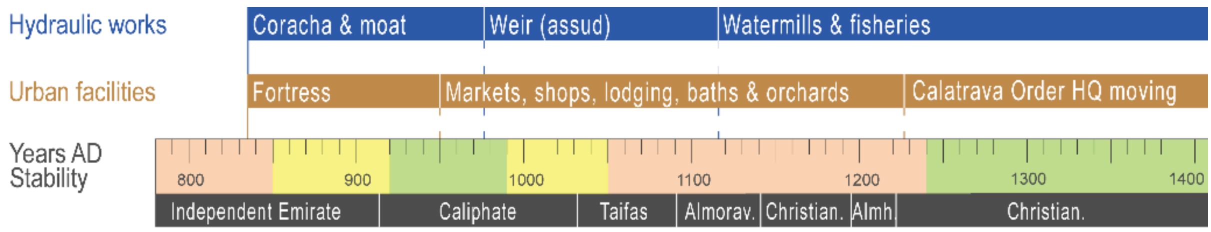


**Figure 4.** Calatrava works references and stability factor timeline

Regarding the optimum conditions to develop civil works, Figure 4 summarizes the relevant facts since Calatrava’s foundation by defining a stability parameter based on the likely political and social circumstances. Unrest periods between independent Toledo and centralized Cordoba, either during the Emirate or later petty states, or later holy and conquering war are considered not favourable (red). On the contrary, the early Caliphate and definite Christian domination of the region are rated as favourable (green), whereas transition periods before and after the Caliphate would be intermediately rated (yellow).

**Table 1.** Essential watermills characteristics by 16$^{th}$ c. and proposed genesis

| # | Asset | Typology | Ownership; [earliest ref. date] | Winged coef. | Head [m] | Head’ [m] | Design pattern |
|---|---|---|---|---|---|---|---|
| 1 | Zorreras | 1 FM | Salinas Earl, built by 1596 (Dadson, 2007) | 1,1 | 0,5 | | |
| 2 | Arquel | 2 MS | Salinas Earl, recently bought to San Juan Or. | 1,7 | 1 | 1 | Original |
| 3 | Zuacorta | 2 MS | San Juan Order; [1245] | 1,3 | 2,5 | 3,5 | Original |
| 4 | Parrilla | 3 MS | Calatrava Order (50%); Dominicas Monastery C.Real (25%); Private (25%) | 1,1 | 1 | | |
| 5 | Máquina | 2 MS | Daimiel commendarie (Calatrava Order) | 1,4 | 2 | 2,5 | Original |
| 6 | Curuenga | 4 MS | Daimiel com. (50%); Dominicos Monastery (25%) & Private (25 %) | 1,1 | 0,5 | | |
| 7 | Griñón | 5 MS | Salinas Earl, Villarrubia Master. Leased to Mr. Roque; [1150] | 1,5 | 2 | 2 | Original |
| 8 | Molemocho | 4 MS | Mesa Maestral Calatrava Order; [1489]* | 1,4 | 2 | >2,0 | Original |
| * | Gaspar Rótulo | No data | No data | 1,3 | -0,5 | 2 | Original |
| 9 | Pte Navarro | 4 MS & 1 recent WW | Daimiel commendarie; [1509]*; [<1422] known as Yamatto** | 1 | 2 | | |
| 10 | Flor Ribera | 2 MS & 2 WW | Mr. Antón de Castro. Probably built by 1533* | 1 | 2 | | |
| 11 | Alzapierna | 3 WW | Mr. Gálaso Rótulo; [976 & 1147] | 1,2 | 2 | 2 | Original |
| 12 | Malvecinos | 2 WW | Mesa Maestral Calatrava Order | 1,3 | 2 | 2 | Original |
| 13 | La Torre | 2 WW | Malagón Duchess [1255] | 1,2 | 1 | 1 | Original |
| 14 | La Celada | 2 WW | Mesa Maestral Calatrava Order; [1296] | 1,3 | 1 | 1 | Original |
| 15 | Emperador | 3 MS | Since 1543 to Toledo Nobel Maidens; [1183] | 1,2 | 1 | 1 | Original |
| 16 | Pte Nolaya | 3 MS | Dominicas Monastery Ciudad Real*; [1257] | 1,2 | 1 | 1 | Original |

 

As proposed, Alzapierna asset had to be erected the latest by mid-9th c., later regional unrest would have not eased the implementation of many units until the Caliphate period, when the system had to be developed and reached its maturity. This hypothesis also agrees with that firm administration capable of supplying the necessary resources to undertake such works, becoming oriental despotism a reality in La Mancha.

Unfortunately, the only possible genesis particularization can be drafted following the pristine hydraulic design, with no apparent interference between units (Doncel Fuentes & Florín Beltrán, 2020) and rated in about 1.5 meter for helix type milling stones, and one meter for vertical waterwheels. Table 1 summarizes the whole system as reported by the 16th c., establishing a categorization for those units theoretically operating with no interferences and with a defined weir typology, as follows:

- Winged or curvature layout coefficient = Weir crest length / Distance between weir abutments. Assuming straight for values below 1,1.
- Available hydraulic head [meters]. "Head" assumes every unit as described on current morphology, whereas Head' is obtained only considering the proposed original units.

According to the presented assumptions, nine out of sixteen units configured the pristine system, with no evident hydraulic interference under normal hydrologic conditions, and sharing a common weir plan design focused on hydraulic efficiency. This system was planned under an integral understanding of the system's hydrodynamics, where available hydraulic head within cascade dams was the limiting factor.

Reviewing the assets with low winged weir coefficients, (1) Zorreras was the last unit built by the Earl of Salinas (Dadson, 2007) powering a fulling mill with limited production; (3) Curuenga was reported in 1530, soon after opening, by Griñón's owner for reducing its production (Jérez García, 2005). This impact is arguable as the most penalized watermill is that one located upstream for reducing the available head.

Next is (9) Puente Navarro built by the mid-16th c. that flooded an asset located 1.5 Km upstream with winged weir, known as La Quebrada or Gaspar Rótulo watermill (Celis Pozuelo, Mediavilla López, Santisteban Navarro, & Castaño Castaño, 2019). Despite of the construction date reference for (10) Flor de Ribera, the available head infers that it was part of the original system, regardless the winged coefficient to make the exception that proves the rule.

Besides, the hydrology of the Guadiana Springs during the Middle Age had to be hyper steady as the 16th c. description shows, and like the earliest metering of a few cubic meters per second (Castro González, 1854). This fact would have influenced the trapezoidal cross section weir design, with analogue slope in both upstream and downstream sides. Flooding events were rare in the upper's river reach down to (8) Molemocho, where most of the watermills could manage the flow by the own vents. However, downstream from meeting the irregular Ciguela River at (9) Puente Navarro, watermill's outlets were insufficient to alleviate the coming flow and had to discharge through the weir's crest.

The morphology of the river reach can be divided into two different sections: the upper from (1) Zorreras down to (8) Molemocho with a riverbed gradient of about 1%; and the lower, from (9) Puente Navarro to (16) Puente Nolaya the gradient decreases to 0.6%. This characteristic summed to the mentioned hydrological risk could have determined the original machinery: the watermills of the upper reach equipped helix turbines, whereas the lower mounted vertical waterwheels as this type demands less head and more flow than the first. Finally, just (8) Molemocho or (3) Zuacorta could have housed a norse type according to the available hydraulic head. But this option is quite remote, as that available steady and large flow would have been wasted with this hydraulic machinery.

## 6. CONCLUSION

Iberian hydraulic technology began in La Mancha four thousand years ago through such ingenious and fortified water-well known as motillas, as result of an adaptative engineering during a probable extreme draught. Some of these works are located near the Guadiana River Springs, a past natural phenomenon that used to make an oasis in the middle or the arid plain.

Apparently, some of the system's units could be associated to the Roman period, but this possibility has been dismissed due to the own weirs' typology but overall, the watermills were basically an extravagance by that time. The coming Barbarian period is uncertain, as the hydraulic industrial revolution had commenced in the Mediterranean basin, but the Iberian unrest conditions did not favour a solid hydropower development.

The acquisition of culeb watermills by Al-Hakam I in the early 9th c. represents the kicking-off for the mainstream implementation of hydro machinery in Iberia, necessary to manage and control the grain milling. This process intensified at the end of the first millennium, during the Andalusian Caliphate, when every necessary requirement was fulfilled: social, technological, and economic. Iberian rivers were profusely colonized with diversion weirs and waterwheels, used either for irrigation or industrial applications that boosted the productivity and economy.

The foundation of the Umayyad Calatrava brought out the first multipurpose riverine weir of La Mancha. It powered the watermill, flooded the defensive moat and the urban supply intake, as allowed to cross the marshy riverbed. Most of the other hydraulic schemes share a similar engineering concept, with a small weir with a winged layout to gently point the flow into the vents. These works assembled a harmonious system adapted to the environmental conditions with no operating disturbances among them.

Such achievement was reached thanks to a concise morphologic and hydrological understanding that even conditioned the type of machinery installed in every watermill. Then, the upper reach with an average gradient of 1% would have originally embraced (2) Arquel; (3) Zuacorta; (5) Máquina; (7) Griñón and (8) Molemocho, mostly equipped with helix turbines suitable for steady flows. On contrast, the lower section with 0.6% of slope was subjected to more irregular flows, so vertical waterwheels were mostly mounted in (10) Flor de Ribera; (11) Alzapierna; (12) Malvecinos; (13) La Torre; (14) La Celada; (15) Emperador and (16) Puente Nolaya.

Subsequent Christian conquest of the region caused an appropriation rush of these industrial assets, as the establishment was fully aware of their economic importance. Progressively, more and more watermills were implemented and enlarged beyond the carrying capacity of the upper Guadiana River reach, jeopardizing the operation of the whole system.

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