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Hydraulic Approach into Olden Agricultural Aqueducts at the Mexican Region of Zacatecas

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Abstract: Civilizations have been able to bloom because of the way they have been historically associated with water resources, especially in seeking strategies to ensure a supply to diverse sectors that require them. Thus, challenges in satisfying water demand are shaped by the particular epoch and geographical area. In this sense, Roman engineering represents a new view of waterworks construction. Above all, it concerns building arched structures to convey water from supply sources to cities; even the hydraulic technology developed by Romans would transcend beyond the time this empire ruled the world. Consequently, this paper shows a brief outlook of some hydraulic systems in Asia, Europe and America settled thousands of years ago. Additionally, a historiographic approach is made for several aqueducts built within the limits that currently constitute the state of Zacatecas during colonial times and independent Mexico in order to evaluate their transcendence for mining, agriculture, and cattle. In addition to the allusion to historical context, the main goal has been to evaluate the hydraulic design of eight olden aqueducts based on current engineering approaches, with the purpose of typifying coincidences between constructive procedures inherited from Roman culture and those used by Spanish conquerors to erect similar civil works in this region.

Keywords: roman aqueducts architecture; irrigated agriculture; hydraulics engineering design; Mexican historiographic; cultural heritage

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1. Introduction

Water, due to its importance for the subsistence of human beings, has transcended as that indissoluble natural element to the progress of every civilization; even Thales of Miletus, Heraclitus, and Pythagoras considered it the genesis of all things. Beyond its intrinsic meanings, it was considered as a primary factor in driving the development of societies. Consequently, deciding on the best place to settle involved discernment about potential supply sources, especially availability and accessibility, which entail multifactorial challenges that over time have been addressed from different approaches. Therefore, it is essential to refer to the evolution of humankind itself to understand how they were faced in different epochs. In this context, Vitruvius Polion, supported by observation and Greek books, offers a thorough study where he first explains how to find water and, second, how to evaluate its quality [1]. As for water affordability, harvest and water conveyance systems provide a historical journey linked to numerous hydraulic works (from different times and regions) developed for water supply and sanitation services. Many research studies have documented a series of finds that evidences the presence of hydraulic systems whose construction dates back several thousand years.

It was in ancient Mesopotamia (4000 B.C.) where one of the first agricultural irrigation arrangements was conceived [2,3]. Moreover, archaeological evidence attests to a progressive technological breakthrough in practices related to the storage and use of water from the Nile River during the Egyptian Pharaonic era (3500 B.C.-640 A.D.). Indeed, Egyptians cultivated about 800,000 hectares of wheat, barley, papyrus, flax, henna, fruit trees, and horticultural crops in a region with an adverse climate for irrigated agriculture [4]. It also highlights the ancient Chinese culture that around 2000 B.C. was already organized in cities with well-defined territorial order. Certainly, establishing towns in the vicinity of rivers was convenient, as it implied less effort when supplying water to the population, but at the same time such proximity entailed frequent flooding risk, a condition that motivated the construction of hydraulic works to alleviate floods caused by rainfall [5].

In Rome, long length aqueducts were so relevant that even Pliny the Elder, for example, considered them an incomparable marvel and, therefore, nothing more worthy of admiration in the whole universe [6]. During this civilization, numerous hydraulic structures (bridges, arcades, closed pipes, tunnels, cisterns, elevated tanks, inverted siphons) were developed to use underground sources, often located several kilometers away from the cities. As a whole, they gave rise to hydraulic systems known as aqueducts. Through manuscripts, such as those by Vitruvius and Frontinus, it is possible to understand aspects of their planning, operation, and maintenance [7–9]. Aqueduct location was mainly based on economic, social, and geographical factors, and its edification intended to improve population life quality at urban centers. Due to the immense water volume they conveyed daily, many of these waterworks had to span a considerable geographical space between supply sources and distribution areas, so it was common to encounter different topographic conditions along their trajectory. Therefore, differences in elevation and an appropriate slope were decisive factors in aqueduct construction. Consequently, water was carried underneath the ground surface, on the ground surface, or above the ground surface, reaching significant heights [10,11]. Hence its sheer magnitude, a fact that even made them an expression of civic pride and, to a great extent, the trigger that drove the development of water engineering and hydraulic technology [6,12].

Despite traces of aqueducts from societies older than Roman, the best-documented antecedent due to its majesty corresponds to the last one [6]. The first aqueduct was constructed during the 4th century B.C., followed by 10 more within 500 years. Altogether, they conveyed more than 1 million cubic meters daily to supply around 500,000 inhabitants [13]. This means a per capita volume distribution of 2000 L per day, far above current standards, which at most reach 200 L per inhabitant per day (10 times less than in the past). At that time, however, priority for water access was given to public buildings, thermal baths, monumental fountains and a fountains network that supplied the population. Thus, it was a common practice to reserve considerable volumes, on the one hand, for privileged social classes that consumed it in their private gardens and pools, even free of charge; and, on the other hand, for economic activities developed in mines, mills, and farms. This restricted water access to the most vulnerable social sectors, forcing them to obtain a usufruct right, a procedure that concluded with a unique payment or an annual fee [14]. Regarding this aspect, it is worth mentioning that these criteria have been modified over time, especially since the Universal Declaration of Human Rights enactment in 1948, which includes access to water as one of the fundamental rights for all world inhabitants.

Concerning Amerindian civilizations, specifically Teotihuacan, Mayan and Aztec cultures that bloomed in Mesoamerica, there is evidence of canals, underground cisterns, and even ground-level aqueducts built with dirt, stones, and wood being used. Although aqueducts in Mexico date back to the early 15th century [15], since 1527, these structures were made with construction techniques similar to those engaged by the Roman culture, according to testimonial evidence [16,17]. After the Spanish conquest, arched architecture coming from Europe spread its use in the New World; Spaniards remodeled the Santa Fe aqueduct, a pre-Columbian hydraulic work, following their construction criteria. In addition, the Zempoala Novo-Hispanic aqueduct (erected since its inception using Spanish experience) is the oldest known in this region [18]. Nevertheless, as happened to the empire that dominated Europe and Asia, aqueducts reflected an evident social segregation. An example is the Valladolid aqueduct (built in 1549) that supplied water to homes of the elite at a low cost and without major bureaucratic complications, while the rest of population underwent an arduous and costly process to obtain an exemption to use it [19]. Of all the aspects that encouraged aqueducts construction, here we highlighted the rise of haciendas, the vast orographic and climatic composition of the territory, and the severe droughts.

The immensity and wealth of the New World promoted expeditionary crossings that spanned a massive territory, forcing the shape of settlements with different characteristics. European-style haciendas were part of these socioeconomic schemes; and being imposed by the Spanish crown, transited a gradual process of drastic social domination, broadly opposed by the resistance of native societies. Apart from damages left by colonizing armies, it is evident that for conquerors coming from Old World, exploiting fertile lands and subsoil represented opportunities for great enrichment, especially since labor force was guaranteed to carry out agricultural, livestock and mining tasks by oppressing indigenous communities [20]. In addition, required waterworks to provide water for the aforementioned productive activities were also built with work of those under royal edicts.

By way of Northern colonization progressed, mineral deposits were discovered, favoring agriculture and cattle raising. Eventually, it led to the emergence of haciendas and ranchos as a reference of rural properties that grouped extensive territorial units for cultivars and animal breeding, whose production supplied part of New Spain. Speaking of Zacatecas, the hacienda heyday took place throughout the 18th century; nonetheless, the concentration of huge land extensions for a few people lasted until well into the 19th century. In addition to economic prosperity, hacienda owners sought to preserve their lineage, and consolidate a vice-regal aristocracy with the main interest of monopolizing all income sources (primordially mines and land), even in opposition to several laws enacted to curb the abysmal disparity between privileged and unprivileged. In spite of this, deprived people who labored in them demanded to become independent towns, and thus caused the fragmentation of large estates; but in parallel, communal lands of indigenous peoples began to fall in value [21,22].

Somehow, it has already been pointed out the historical relevance of waterworks to the consecution of every anthropogenic productive activity, making emphasis on aqueducts originating from Roman culture. Concerning Mexico, particularly within boundaries that today comprise Zacatecas state, evidence suggests arched architecture was often used to convey water from a supply source to an agricultural irrigation area. Water was abstracted from rivers and springs that sprouted on hills slopes bordering places. An extra issue, none helpful from a historical comparative point of view, is the lack of reliable information about technical criteria applied for hydraulic design, as well as constructive guidelines with which arch-style waterworks were built during Zacatecas haciendas time. Likewise, many studies document the knowledge existing in the Roman Empire about the physical phenomenon of carrying water from one place to another. However, given the limited information that may be found on aqueducts design and operation procedures [10], this claim is mainly based on archaeological evidence of hydraulic works built at that time, subject to an assessment that comes from current fluid mechanics fundamentals.

The Roman aqueduct system evolved for more than 500 years, with the first being the Aqua Appia, built around 313 BC [12]. Its route began at a water source and ended at a distribution basin (*castellum divorsium*), from where an urban distribution system began, which was operated by a specific flow measurement and control structure [23]. In general, the different analytical expressions show various degrees of consensus related to contributions attributable to this civilization. Everything indicates, without any objection, that they are the ones who, for the first time, used arches as a structural stability element for civil works and developed hydraulic concrete; they are also pointed out for having improved technology coming from other civilizations, especially as far as hydraulic works are concerned. However, these same evaluations disagree as to the mode for achieving such innovations. For some, experimental practice under trial and error was the pattern that prompted their achievements; for others, it was their advanced knowledge in fluid mechanics and hydraulic engineering [7,24–26].

As regards tracking patterns that point to standardized criteria to design, build and operate aqueducts, Fahlbusch [27], after analyzing several kinds of these waterworks, found that, although the chosen size of a cross-section depended on allowing the pass of an estimated discharge, it was also a selection criterion that ensured the transit of repair and maintenance personnel. In addition, channel width and length could vary along an aqueduct, while cross-sections were kept constant in a considerably long reach extent. On the other hand, authors such as Wolfram and Lorenz [28] and Motta et al. [29] have focused on the study of geometrical relationships of various aqueducts erected by this past culture. Findings of the first cited documentary references indicate a close harmony between different geometric compositions from the point of view of structural stability of civil works; while with results reported by the second reference, it is stated that there is no statistically significant correlation between channel elements that give rise to the delimitation of the different geometric relationships on which the hydraulic analysis of free surface flow is based. However, other reports indicate that longitudinal channel slope was subject to a range between 0.2 m km^{-1} and 5 m km^{-1} [30], even though only a cross-section sizing was used as a design criterion to transport a given flow [9,31].

In the Zacatecas northern region, hydraulic systems construction with technology was brought by colonizers derived from discovering important mineral deposits, mainly silver; while in southwestern areas, interests were in large extensions of fertile land and vast timber resources. Beyond reasons that gave rise to founding of communities to house social structure, extractivism itself forced agriculture and livestock development. Thus, in each territory water would be a pivotal element to trigger commodities generation and food production for population sustenance. In short, Spanish presence in this region is essentially explained by the above considerations; however, its achievement depended on infrastructure in accordance with an increase in demand for goods and services. As for hydraulic works, water supply systems of Mesoamerican origin continued to be used [32]; but aqueducts edification with Roman architecture stood out as a new construction technique to carry water, which would help to take advantage of supply sources located at considerable distances from productive centers and thereby increase international trade and expand agricultural frontiers [17,33].

In an endeavor to inquire about conveyance waterworks systems that were used over the course of 150 years as part of irrigation practices adopted by certain croplands in Zacatecas, this study accounts for specific agricultural water management scenarios on the basis of specific deductions arising from theoretical and practical approaches now framing hydraulics design field. For such aim, a hydraulic prospection begins by joining scientific grounds and criteria for operating water conduction and distribution networks under a scheme of local manual control that prevails at present, specifically considering relations between flow velocity and maximum probable flow rate to be handled in water networks. Based on the foregoing, the following particular objectives were stated: (a) to conduct a comprehensive historical review of documents in archival sources, in order to delve into farming patterns that prevailed in the 19th century and the first half of the 20th century, especially those related to water use for crop production; (b) to carry out a field survey aimed at testing, on each site, specific traits of water catchments, aqueducts, and other hydraulic works devoted to irrigated agriculture back then, and (c) to assess, through fundamental principles of contemporary hydraulics of open channels, water volumes delivered to croplands by olden aqueducts.

2. Materials and Methods

2.1. Delimitation of Study Area

The state of Zacatecas is located in Northern Mexico, between extreme geographic coordinates/points 21°01′45.0″ N latitude and 100°43′34.3″ W longitude, and 25°07′21.5″ N latitude and 104°22′56.4″ W. The West and Southwest are part of the Sierra Madre Occidental Mountain range conformed by plateaus reaching 2850 m above sea level. The Central region is set in the Mesa Central Highland, with valleys around 1000 m above sea level. The North is part of the Sierra Madre Oriental Mountain range, where the highest elevations of the state are located, reaching an altitude of 3200 m above sea level [34]. Zacatecas' climate is semiarid, with minimum and maximum mean monthly temperatures of 6.5 °C (January), and 29.6 °C (May), respectively; an average annual precipitation of around 550 mm, of which 80% occurs from June through September. It is worth mentioning that the above values (especially for rain) change considerably when analyzed on a smaller geographic scale; thus, on average, in Southeast rainfall yearly reaches up to 1000 mm per year, meanwhile in North scarcely registers 300 mm [35].

Eight olden aqueducts of some productive cropping areas in Zacatecas were evaluated in terms of crop water requirements and water management, both aqueducts and plots (Figure 1). Nevertheless, the lack of detailed information about procedures to define water volumes, as irrigation concept, that were needed to compensate for water demanded by crops at that time, make it necessary to resort to the current reasoning on crop evapotranspiration, effective precipitation, and water use efficiency concepts. Therefore, this work took into account some recent contributions on the subject, carried out in regions surrounding each estate farm in question. In that sense, the findings of España [36], Flore-López and Bautista-Capetillo [37], Bautista-Capetillo et al. [38], Mojarro et al. [39], Luna [40], De León and Robles [41], and Allen et al. [42] have been a reference point to infer irrigation water management. Due to temporal differences between previous literature and conditions prevailing then, it is appropriate to consider inherent reservations; notwithstanding, computations and also determinations derived from alluded methodologies are sufficient for the ends pursued here.

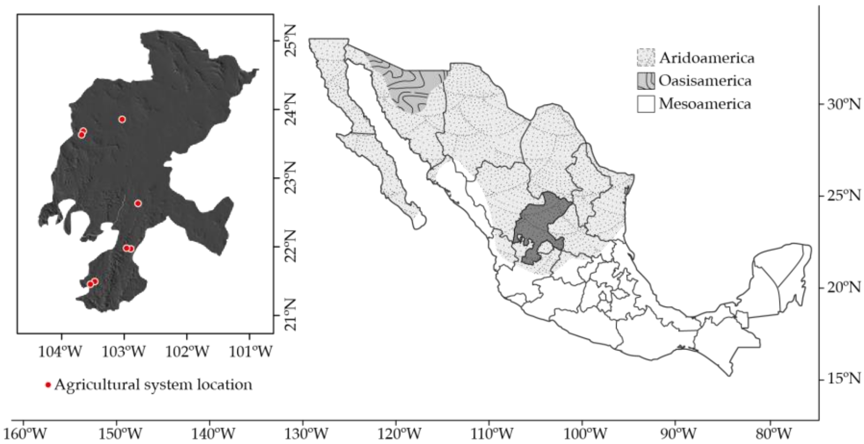


Figure 1. Agricultural systems location under study. On the map showing current political division of Mexican Republic; Mesoamerica, Aridoamerica, and Oasisamerica regions are overlapped.

2.2. Historiographical Review

Historical context is founded on directives set forth by Florescano [43], in particular those associated with explanations of social, economic, and productive systems of the past, under the shelter of present-day reasoning. For this aim, the initial phase of this research focused on a comprehensive literature review, especially on documentary information on water and land corresponding to the haciendas period and which are now in the Historical Archive of Zacatecas custody. In addition, later, an in situ rating was made to enhance the in-depth knowledge in terms of hydraulic systems used for agriculture practiced at that time. In this sense, interviews were performed with authorities responsible for keeping a historical chronicle of places covered in this paper. Additionally, a topographic assessment was carried out in an attempt to ascertain the geometric characteristics of eight olden aqueducts, as well as to typify topographical forms of agricultural zones to which they supplied water. Thus, to get an approximation to ground contour lines conditions in irrigated agricultural farms, as well as longitudinal slope and cross-section of hydraulic conduction and distribution waterworks for all agricultural irrigation systems included in this study, planimetry and altimetry surveys were undertaken by a total station Topcon manufacturing, model OS-105 with an accuracy of 5″. Field information gathered and currently acknowledged approaches for open channel design were the basis for inferring flow rates applied to agricultural irrigation.

2.3. Equations Ruling Surface Flow for Open Channels Design

A free surface flow finds its physical interpretation in fundamental conservation principles of mass, energy, and momentum. Theoretical foundations for each case are discussed in numerous texts on the open channel hydraulics topic [44–47]. However, the lack of analytic frictional resistance depiction calls for adopting alternative methods, which in many cases are a consequence of experimental formulations [48,49]. Due to the scope of this research, solely equations ruling steady flow to open channels design for uniform conditions are addressed, with particular emphasis on a cross-section of rectangular geometry. In evaluating discharge in an open channel under a uniform flow approach, two main hydraulic premises must be kept in view: (1) depth of flow, water area, velocity, and discharge at every cross-section along the length of a channel reach are constant; and (2) energy line, water surface, and channel bottom are parallel; in other words, all slopes are equal. For practical purposes, mean velocity computation into turbulent conditions underwent an important breakthrough as a result of achievements reached by Chezy in this subject around 1775, which are summarized in Equation (1). Subsequently, several equations have been proposed to estimate flow resistance, with the Manning equation as one of the most common, partly owing to the ease of being applied to real cases with fairly acceptable accuracy (Equation (2)).

$$\mathrm{V} = \mathrm{C}\,\sqrt{\mathrm{R}\,\mathrm{S_0}} \tag{1}$$

$$\mathrm{C} = \frac{\mathrm{R}^{\frac{1}{6}}}{n} \tag{2}$$

where V is mean velocity, R is hydraulic radius, S_0 is energy line slope, C is a flow resistance factor known as the Chezy coefficient, and n is the Manning roughness coefficient whose dimensions are [$L^2\ T^{-1}$], [L], [adim.], [$L^{1/2}\ T^{-1}$], [$L^{-1/3}$ T], respectively. By rearranging Equations (1) and (2), afterwards bounding the outcome to the continuity equation for a steady flow, yields an expression to estimate flow rate (Equation (3)).

$$\mathrm{Q} = \frac{1}{\mathrm{n}}\,\mathrm{A}\,\mathrm{R}^{\frac{2}{3}}\,\mathrm{S}_0^{\frac{1}{2}} \tag{3}$$

where Q is flow rate, whose dimensions are [$L^3\ T^{-1}$], and A is water area of [L^2] dimensions. For specific rectangular cross-section cases, values of A and R are determined from Equation (4); meanwhile, b and y_n, in that order, correspond to channel bottom width and normal depth; also, notice that dimensions of both variables are [L].

$$\begin{aligned} \mathrm{A} &= \mathrm{b}\,\mathrm{y_n} \\ \mathrm{R} &= \frac{\mathrm{b}\,\mathrm{y_n}}{\mathrm{b}+2\mathrm{y_n}} \end{aligned} \tag{4}$$

As a complement previously indicated, when reasoning about discharge capacity in an open channel, it happens that for the same flow rate it is possible to choose, for a certain cross-section, a wide range of alternatives to concretize desired geometry sizing; however, for each cross-section, there is a hydraulically optimal geometrical shape in which water conveyance is maximum. If slope, roughness coefficient, and water area are fixed values (from hydraulics viewpoint), a minimum perimeter section represents an efficient section as it conveys maximum discharge. This channel cross-section is called the best, maximum efficiency, or the most economical hydraulic section. The relationship between rectangular geometric elements (bottom width and flow depth) to conform to a better hydraulic section is shown in Equation (5).

$$\begin{gathered} b = 2\,y_n \\ A = 2\,y_n^2 \\ R = \frac{y_n}{2} \end{gathered} \tag{5}$$

Regarding plot surface flow, discharge through furrow depends on its section, its hydraulic conditions, land longitudinal slope, and factors associated with soil erodibility. Hence, the U.S. Department of Agriculture [50] stated a simplified furrow design methodology (Equations (6)–(12)), this study takes into account procedure steps suggested by Rendón et al. [51] (a detailed analysis can be consulted in mentioned references). First, a unit stream is defined; next, the number of furrows to be irrigated simultaneously is computed. Additionally, the determination of a gross irrigation table is needed, thus unit irrigation volume and irrigation time are obtained. Finally, maximum non-erosive and optimal discharges are calculated.

$$Q_u = \frac{Q_g}{p} \tag{6}$$

$$N_f = \frac{Q_a}{Q_g} \tag{7}$$

$$L_g = \frac{L_n}{E_a} \tag{8}$$

$$V_u = L_g D \tag{9}$$

$$T_i = \frac{V_u}{Q_u} \tag{10}$$

$$Q_{max} = \frac{0.75}{S_0} \tag{11}$$

$$Q_{opt} = \frac{Q_u}{D} \tag{12}$$

where Q_u is unit stream [$L^2\ T^{-1}$], Q_g is furrow irrigation discharge [$L^3\ T^{-1}$], p is wetted perimeter [L], N_f is the number of furrows simultaneously irrigated, Q_a is the total discharge handled by each plot [$L^3\ T^{-1}$], L_g is gross irrigation table [L], L_n is net irrigation table [L], E_a is application efficiency, V_u is unit irrigation volume [L^2], D is irrigation length [L], T_i is irrigation time [T], Q_{max} is maximum non–erosive discharge (lps directly), S_0 is furrow slope [$L^1\ L^{-1}$], Q_{opt} is the optimal discharge to irrigate a furrow square unit [$L^3\ T^{-1}$].

2.4. Crop Water Requirements

Several methodologies are used to estimate water required by crops, among the most common is one that considers crop evapotranspiration calculated from reference evapotranspiration and crop coefficients that vary according to the phenological development stages of each crop in particular [42], as Equation (13).

$$CWR = ET_c = ET_0 K_c \tag{13}$$

where CWR is crop water requirement [$L\ T^{-1}$] to compensate for the losses of water through evapotranspiration, it is generally estimated from crop evapotranspiration as the product of reference evapotranspiration (ET_0 [$L\ T^{-1}$]) and a crop coefficient (Kc [adim]) that varies along the crop phenological stages. ET_0 was calculated based on the application of the

Hargreaves-Samani equation (Equation (14)), which involves factors such as solar radiation (Equation (15)), extraterrestrial radiation, and temperature [52].

$$ET_0 = 0.0135\ R_s(T_{ave} + 17.8) \quad (14)$$

$$R_s = KT\ R_a(T_{max} - T_{min})^{0.5} \quad (15)$$

where R_s is solar radiation {11.6 [M L^2 T^{-2}] [L^{-2} T^1]}, R_a is extraterrestrial radiation {11.6 [M L^2 T^{-2}] [L^{-2} T^1]}; T_{ave} is daily average air temperature (°C); T_{max} is daily maximum temperature (°C); T_{min} is daily minimum temperature (°C); and KT is an empirical coefficient considered as 0.162. In order to obtain crop evapotranspiration, K_c values were considered as those proposed by the Food and Agriculture Organization of the United Nations (FAO-56 manual), who has defined four phenological stages (initial, development, mid-season, and late or final stages), by estimating three Kc values (at the initial, Kc_{ini}; mid–season, Kc_{mid}; and late–season, Kc_{end}), and connecting straight line segments through each of the four growth stages [42].

2.5. Efficiency Assessment for an Irrigation System

Irrigation performance is measured by employing several techniques [53]. In the case of surface irrigation methods, the water application efficiency ratio (E_a) is mostly used as a performance indicator to evaluate water productivity to the plot level, while the performance at the water supply network level is computed by the water conveyance efficiency indicator (E_c) [54–56]. In order to evaluate water losses along a conveyance network, E_c is calculated as the ratio between outflow discharge and inflow discharge into several segments of lined and outlined canals that conform to the channel network. Regarding water use at the farm level, the ratio between water depth needed by the crop and water depth delivered to the field must be tested along the crop growing season.

3. Results and Discussion

The haciendas system imposed by the conquerors Cristóbal de Oñate, Juan de Tolosa, Diego de Ibarra and Baltazar Temiño de Bañuelos conditioned the social, economic, and political structure during the colonial period in the region of Zacatecas. In that sense, haciendas became the dominant way to exploit and manage the abundance of silver and gold in the subsoil, as well as agricultural and livestock activities. In 1550, during the colonial period, several ordinances were enacted following the visit of the oidor Hernán Martínez de la Marcha, allowing the regulation and organization of productive activities [57]. Due to the rapid mining development, particularly in Zacatecas, the establishment of agricultural and livestock areas was crucial in order to satisfy the needs of great mining centers (San Martín, Sombrerete, Chalchihuites, Fresnillo, Mazapil, Charcas, Nieves, Pinos, Ojocaliente, and Ramos). During this period, an important route was also opened: El Camino Real de Tierra Adentro. According to Rivera Bernárdez [58], the search for permanent water sources was essential, since the Arroyo de la Plata, that crossed the City of Zacatecas, turned out to be extremely unstable. In the 16th century, the water used on haciendas was obtained from streams, springs, wells, and rainwater harvesting [59]. Later on, major disputes and complaints regarding the use of water in the mining, agricultural, livestock, and domestic sectors began, hence the concern to build large works to capture surface runoff during the rainy season [60].

Prior to the Spanish arrival to the New World, agriculture as a well-structured livelihood has been almost exclusively practiced in Mesoamerican region. It was chiefly focused on maize growing, interspersed with cultivars such as beans, chili peppers, and squash, under agrarian production systems aimed at making utmost profit from arable land and labor force enrolled in farming tasks. The responsibility for this last aspect first fell on the entire family unit giving rise to a model of subsistence agriculture, then, over time, it was transformed into a model of commercial agriculture working under favorable cooperative associations [33]. In the region comprising pre-Hispanic Aridamerica, climatic conditions hindered the development of agricultural societies. Most of its native peoples were nomadic, living by hunting, fishing, and gathering fruits or roots. Seasonally they settled in small riverside colonies to benefit from available water to allow them to practice subsistence agricultural pursuits [61]. Conquers interests followed different paths and many of them came precisely to this inhospitable region—which included much of Zacatecas territory—in almost any sense of speaking. Silver and gold in abundance, vast plains for agricultural practice, appropriate technology to exploit groundwater and thus compensate for poor rainfall regimes. Everything was in place for Mexico, and particularly Zacatecas and Guanajuato regions contributed considerably to Spain becoming a world power in the 16th century, due to its agricultural and mining system. However, the heyday and splendor that the world had for silver declined towards the end of the 18th century as the Industrial Revolution in England led to oil taking the place that silver had held for many decades.

Irrigation systems implanted in farmland holdings (haciendas, ranchos, or orchards) were primarily conformed with groundwater and surface water catchment sources, conveying works, distribution works, collection and division water structures, and in some cases lifting devices to bring water from one waterworks to another. It should be noted that during field visits made for the sake of this investigation, no evidence was found about structures that might have been used for discharge control purposes, less still for flow measurement. Figure 2 shows a sketch that illustrates, broadly speaking, supply water systems arrangement for agriculture practiced at that time. From the perspective of water sources to supply irrigation areas, they came from mountain springs located at a higher elevation than farming plots and, in this way, water flowed by gravity. Nonetheless, in a few cases, springs sprouted near to plains suitable for agriculture; but also, in situ evidence shows that water was withdrawn from rivers and streams, and then stored in reservoirs. Water volumes were delivered via lined channels to an acequias distribution network in charge of taking water to convenient topographical points so water could circulate by some surface irrigation technique inside plots. Thus, water resources availability and land in plenty gave rise to irrigation farm exploitations fed with water provided from locations where steep terrain relief is no longer a topographic constraint to approach water by gravity.

In light of the above, water allocated to haciendas and ranchos discussed here, apart from satisfying crop requirements or watering livestock, and even supplying the population itself, was stored in reservoirs and then used during the dry season. Such an assumption arises from climatic conditions of Zacatecas, which are characterized by summer rain, since around 80% of annual rainfall befalls between June and September [62]. Clearly, these months of higher humidity bring rainfall that compensates for a set volume of water needed to cover distinct uses; and, in turn, makes it possible to produce a larger surface runoff at natural watercourses. On the matter, testimonies remaining in sites tested reveal small reservoirs' construction whose storage capacity was limited to one or at most two supplementary irrigations over a single crop cycle, especially in agricultural estates settled towards the North where rainwater is not plentiful. This agrees with the information provided by the Chronicler of Teul [63] referring to "water houses", which, in a strict sense, were properties expressly established in fertile valleys with the target of farming cropland in the rainy season, but once cultivars were harvested, people moved from places to engage in other sorts of activities.

Regarding the eight aqueducts characterization exposed in this work, findings show that architectural and constructive aspects are similar to each other. They are arched structures built of local masonry (in some cases, brick was also used) joined with mortar; the upper channel for water conveyance, in all cases, has a cross-section of rectangular shape. Typology described converges with those narrated by literature in relation to the same architecture of ancient arched aqueducts developed by Roman culture [9,11,17,64,65] except for height to compensate for topographic differences and length aqueducts studied here came to have to carry water to places where needed [8,10,32]. To assume a value of discharge that could have circulated through these aqueducts, and from this to have an approximate idea of water management in agriculture back then, hereafter hydraulic properties and flow rate for open channels included in this study are given in Table 1.

Figure 2. Schematic representation of agricultural systems (elaborated by authors with photographs taken by themselves).

Table 1. Hydraulic properties and flow rate in eight olden aqueducts.

Aqueduct	b (m)	y_n † (m)	n § ($m^{-1/3}$ s)	S_0 (‰)	A (m^2)	R (m)	Q ¥ (lps)	b_e (m)	y_e (m)	R_e/R	Fr	Flow Regime
Teul	0.34	0.15	0.015	29.61	0.05	0.08	108.3	0.32	0.16	1.004	1.756	SuperC
Haciendita	0.30	0.10	0.025	21.34	0.03	0.06	25.0	0.24	0.12	1.032	0.904	SubC
Custique	0.72	0.25	0.032	NA ‡	0.18	0.15	264.4	0.60	0.30	1.017	NA	NA
Providencia	0.60	0.20	0.015	28.33	0.12	0.12	327.6	0.50	0.25	1.042	1.949	SuperC
Malpaso	1.23	0.95	0.015	4.16	1.17	0.37	2605.0	1.52	0.76	1.018	0.726	SubC
Vergara	1.55	0.91	0.025	3.91	1.41	0.42	1974.0	1.68	0.84	1.004	0.469	SubC
Guadalupe	0.43	0.45	0.015	12.10	0.19	0.15	392.5	0.62	0.31	1.065	0.985	SubC
Pastelera	0.90	0.55	0.015	8.96	0.50	0.25	1231.6	1.00	0.50	1.010	1.078	SuperC

Notes: † Normal depth values were achieved as the difference between depth of channel (d) and freeboard (F): $y_n = d - F$, F = 0.2d [46,49]; § roughness coefficients were proposed taking into account those reported by literature as "normal" values from conditions observed in situ inspections; NA is a not available value; ‡ due to its proximity to Providencia aqueduct, the same slope was considered; A, R, and Q were computed for normal flow conditions by using Equations (3) and (4); ¥ discharge is expressed in liters per second; b_e and y_e were computed from Equation (5); Fr is Froude number [adim]; SuperC is supercritical flow regime; SubC is subcritical flow regime.

As for the flow rate carried by olden aqueducts, results indicate that the figure would have ranged from 25.0 lps to 2605.0 lps while the water area corresponding to each case is nearby 0.03 m^2 and 1.41 m^2. On the other hand, when comparing geometric elements that underpin hydraulic properties A, P, and R, the tendency reflects that channel bottom length is bigger than normal flow depth, although for effects of all practical consideration, strictly speaking, dividing b/y_n yields a proportionality factor around 1 and 3. Thus, except for the Guadalupe aqueduct ($b \cong y_n$), the other seven aqueducts have a channel section whose dimensions are within the $y_n < b \leq 3y_n$ interval. In addition, Table 1 also shows parameters giving rise to a cross-section of maximum hydraulic efficiency for a rectangular-shaped channel in which could be conveyed an equivalent discharge, like that estimated for the actual size of studied waterworks. By contrasting actually constructed and hydraulically optimal cross sections, differences in size were found between the former and the latter. As far as the channel bottom, the outcome revealed an average increment of −0.05 m in the range of −0.29 m and 0.12 m; whereas for flow depth, an average increment of 0.04 m was recorded as a consequence of values that arise onto every aqueduct; the set thus constituted is circumscribed to −0.05 m and 0.19 m as lower and upper limits, respectively.

In light of the above findings, it is inferred that in ancient aqueducts of Zacatecas farmlands, the average geometry of channels was defined by a channel bottom width as small as 5% and by a flow depth as large as 4% with respect to dimensions required for those geometrical elements, that correspond to those of a section of maximum hydraulic efficiency capable of carrying same flow rate. Even more, channel bottom and flow depth combinations normally gather characteristics suitable for associated hydraulic radius to be of a magnitude alike to that calculated by criteria that originate Equation (5). In this sense, Table 1 includes values derived from the Re/R ratio; upon running an exploratory data appraisal, it is possible to observe that proportions oscillate in a range between 0.3% and 6.5%, also registering an average proportionality factor of 2.4%. Based on evidence presented here, it is appropriate to assume waterworks, at least in the case of aqueducts, were designed following certain empirical formulations largely attached to currently accepted design methods due to being developed from theoretical bases and experimental studies rigorously grounded, but this hypothesis must be corroborated from at least two approaches: to investigate deeply on engineering criteria that supported the hydraulic design of water supply works, since at the close of this research stage no documentary evidence on the subject was found, and also to carry out a study from the field of structural engineering in order to rule out that ancient aqueducts were exclusively dimensioned to avoid failures on structural elements, particularly in those places where topographical conditions motivated edification of high arches to overcome differences in terrain elevation.

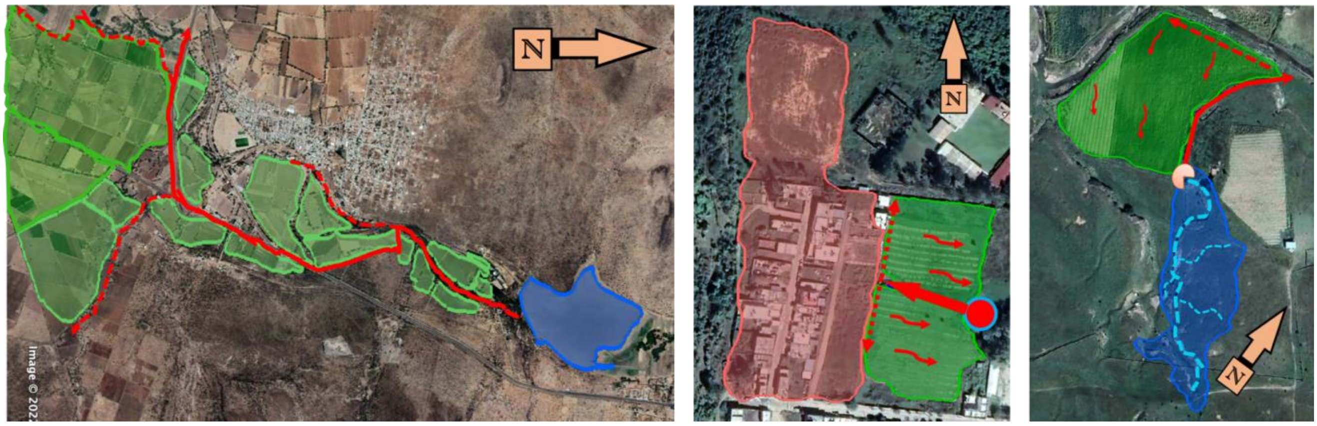
It should not be overlooked that economic criterion has been, and still is a relevant decision factor into civil works construction. In such a way, this consideration should not be left aside when selecting between alternatives to be erected. In the subject matter herein, Malpaso, Vergara, and Guadalupe aqueducts may be emphasized like the ones with the greatest difference in their channel bottom width facing the respective best hydraulic section. Then, if the assumption that at those times there were already procedures to endorse hydraulic design of channels is accepted as true, the economic aspect is the possible justification for cross sections of these three aqueducts. That is, practically any context of a hydraulic nature that tried to define waterworks dimensioning would not have an effect against a greater economic investment because of materials and labor would be expended to build more robust arches to hold up water conveyance works. In other words, no matter how significant have been the savings in a more economical channel construction, it can never be equated with an increase in cost for the concept of other structural elements forming part of an aqueduct of such architectural parameters.

Agricultural Water Management

In some sense, it has already been established that the fundamental objective of channel network operation in an irrigated area is to convey and transfer water resources from supply sources to delivery places, in order to meet a given demand both in quantity and timeliness of irrigation requirements associated with crop water requirements. The operation is concerned with movement and behavior of water within channels system. Thus, the primary function of operation of a channels network consists of the management and hydraulic control (changes in discharge and levels) in its entirety, in order to satisfactorily fulfill its part in guaranteeing the optimum development of the crops. Hence, the greater and more complex requirements imposed on a channel, the more complex it will be to impose a rigorous control scheme. The spectrum of variables to consider when establishing the degree of difficulty involved in operating a channel network is very broad; however, the operating flow rate, number of diversion sites and volumes to be distributed among them, and length to transport it from supply source to all areas where it is required for subsequent irrigation of plots are the most important.

In aqueducts that report this work, three types of hydraulic systems stand out according to irrigated area: (a) surface irrigated agricultural fields by furrow irrigation, whose extension exceeds 200 hectares, a storage source for surface runoff, and a conduction and distribution network with lined canals in its primary system and unlined canals in its secondary and tertiary network (see Figure 3a); (b) surface irrigated agricultural fields by furrow irrigation, with areas of less than 5 hectares, groundwater as supply source, a small length aqueduct carry water to an irrigation ditch (Figure 3b); (c) surface irrigated agricultural fields by furrow irrigation, with area ranging between 2 and 14 hectares whose irrigation is of a supplementary nature, water generally comes from surface runoff and is stored in small capacity reservoirs which are used in the same irrigation campaign, an arched aqueduct of small length that derives water directly to an irrigation ditch (Figure 3c).

When comparing the findings presented here with those of similar evaluations carried out on Roman aqueducts, parallels are observed regarding longitudinal slope of channel bottom. Hydraulic works that transport large flow rates through a network of channels also of great lengths, were built with mild longitudinal slope [9,31]. The Malpaso aqueduct, for example, probably came to transport 2600 lps under a subcritical flow regime (Table 1); that is, at low velocities to allow a better operation of the hydraulic infrastructure in exchange for a cross-section greater sizing. In contrast, as the degree of complexity in hydraulic operation decreases, the flow velocity increases. This can be seen when evaluating Teul aqueduct, a hydraulic work to satisfy water needs of a crop established on a small area, transporting water over a short distance and, in addition, only one user. In this case, discharge of about 100 lps flows under a supercritical condition, so that its velocity is relatively large enough to complicate hydraulic operation if appropriate precautions are not taken to prevent it. However, the above actually says little about the ability to design a canal, beyond empirical formulations, if no practical sense is given to the capacity that such a structure must have to convey a flow rate that will appropriately meet the need.



(**a**) Malpaso (**b**) Teul (**c**) Haciendita

Figure 3. Agricultural systems irrigated by arched aqueducts (elaborated by authors with support from Google Earth© 2022).

Aspects of water supply systems were earlier outlined, from catchment sources to irrigation areas, with particular emphasis on the connection between them: the conveyance waterworks. Hydraulic bases for flow rate carrying have already been covered, and now it is time to deal with agricultural water management, especially at plot level. According to Rendón [51], an agricultural user can manage a discharge between 20 lps and 120 lps, of course, this range is delimited at least by farm size and systems performance which usually is concretized in terms of hydraulic operation and water use efficiency. In an effort to clarify such issues, the next paragraphs describe the insights that emerge from the evidence stemmed in situ as well as from methodological analyses carried out on them. It is worth saying that several productive schemes show similar conditions, in such a way that only the cases of Teul and Malpaso are presented because they are considered representative of the generality that occurred at the time. In the first one, a water management assessment for an irrigated cropland under monoculture conditions is carried out, while in the second one, the same is done, but for an irrigation land on multi-cropping type.

On the agricultural development of Teul, it is important to highlight three particularities: (1) a spring emanating within the estate was the catchment source; however, transferring water from it to a delivery point implied overcoming a difference in elevation such that it was necessary to have a mechanism to do it, probably a wheel driven by animal force fulfilled these functions, (2) the total water volume that circulated through this aqueduct was delivered at a single point and then distributed through irrigation acequias to an irrigation area, and (3) the agricultural surface was devoted to fruit trees production in approximately 2.5 hectares; however, it is also possible that vegetables were irrigated on this farm, but on a small scale. Quince crop was harvested, a fruit of low economic margin when taken to markets without any added value, but that increases its economic performance when transformed into quince paste. In fact, this was an essential product offered by the orchard plantation (as much for local consumption as to commercialize it in neighboring regions), even, in the voice of the chronicler of Teul [63], it was offered in the prosperous cities of Zacatecas and Guadalajara. Now, for a quince crop whose production starts at the beginning of March, the highest dose of irrigation water required by the crop in a 10–day span is around 44.6 mm, this is based on climatic conditions and soil characteristics of the site, ten days between irrigation events, and an application efficiency of 40%. Given this, the hydraulic system that provided water to fruit trees had enough capacity to irrigate the agricultural area in its entirety in sixteen hours, as long as the flow rate was 108.3 lps, even with 50% of that value, it would have been enough to meet crop water requirements in their most critical development stage. Thus, the hydraulic characteristics of an open channel in this aqueduct allowed for the transportation of enough water for the pursued objective, therefore, achieving it depended more on the capacity of the lifting wheel and animal power that drove it. Regardless of what would have prevailed in practice, it certainly is an oversized channel in relation to the flow that it had to carry to meet water needs for fruit trees. In spite of this, the cross-section has adequate hydraulic characteristics because it is a relatively small aqueduct. However, bed slope provokes a fast flow with a relatively high velocity, which could cause water handle problems, especially if hydraulic structures were not built toward the end to control it before water was channeled to irrigation acequias.

It is important to notice that productivity crop quince in this agricultural plot, prior to the arched aqueduct was built, would have been difficult to sustain in terms of economic profitability. Between the spring level and the highest part of the plot, there is an adverse slope of 20‰; with technology back then, it was not possible to overcome this condition of natural terrain to carry water through acequias at ground level. From this argument, rainwater had been the source of water available to cultivate farm; this area has an average effective rainfall, between March and November, of 560 mm, but quince fruit developing between the previous months require a water table depth equivalent to 1058 mm to grow in optimal conditions of humidity. Of course, the above information shows the need to apply something like 50% of water required by crop through supplemental irrigation; however, some varieties of vegetables, cereals and legumes are suitable to be grown only with rainwater.

Unlike the production scheme associated with Teul, the agricultural system linked to the Malpaso aqueduct produced by using water from a reservoir, discharge could be distributed to allow the delivery of a certain volume of water at different points along the channel trajectory. Moreover, a crop variety was established every agricultural season, mainly staple grains and vegetables. Likewise, the agricultural production system handled a flow rate almost 25 times larger and, of course, the irrigated area was also considerably superior. Although it was not possible to determine the cropping area dominated by the aqueduct, Villanueva chronicler [66] estimates that between 200 and 300 hectares were able to be irrigated. Undoubtedly, the complexity degree of agricultural production systems was greater in Malpaso than in Teul. Such asseveration emerges based on own crop phenology. In this way, irrigation planning implied defining for whole cultures spectrum, at least intuitively, sowing date for every crop, water requirements, application doses distributed throughout different crop development stages, and an irrigation schedule to cover the whole agricultural area without detriment to agricultural yields. Likewise, and as a consequence of all this, to establish criteria for waterworks' operating with an emphasis on an adequate control and enough delivery of those flow rates that, on the one hand, allow optimal water productivity and, on the other hand, minimize losses of this natural resource. Evidently, these determinations must be taken into account for monocropping estates, without losing sight that they generally may be simpler to manage than those multi-cropping plantations.

When previous arguments are pondering onto Malpaso irrigated agriculture, outcomes wield a reasoning series as follows. In this region, the average rainfall between April and September is around 370 mm; crops such as wheat, corn, and beans are usually established to complete their vegetative cycle during this lapse. In order to assess the cropping area to be irrigated with water from the aqueduct, guidelines established in literature [41,42] were taken into account for furrows surface irrigation (0.75 m wide and 150 m long), with an incipient water management for both conveyance works and plot itself (irrigation efficiency of 40%). On the other hand, 10-day irrigation intervals were considered throughout the phenological life of each crop and 10 h as characteristic irrigation time. It is pertinent to clarify that the above values are adopted in this work since they are characteristic of the region; in case of furrow dimensions, it is common for farmers to adopt them, while furrow irrigation efficiency and irrigation time are result of evaluations carried out in different plots [37–40]. From the above conditions, it was found that for wheat, with a sowing date at the beginning of April, around 200 hectares would have been cultivated; however, by establishing until the end of the same month, the area would reach 250 hectares (rainfall would allow a 17% reduction in crop irrigation dose, in its most critical stages of water needs). About corn, 300 hectares, even a larger area, would have been cultivated, taking April 1 as the sowing date; postponing the beginning of its agricultural cycle could affect crop yield due to the risk of frost in October. Notwithstanding, by producing both crops at the same time, considering a hypothetical 30-day lag between corn and wheat sowing dates, both could have been established in an area of 300 hectares, even 25 additional hectares of beans, if the proportion of cultivated area between wheat and corn was 60 to 40%. It is worth mentioning that the above has been related to channel capacity (2605.0 lps), so, in addition, the catchment source should have a volume of 1.5 Hm^3 to start cultural practices before cropping season.

It should be remembered that the above assertions are reached by evaluating only a flow operation scheme based on its maximum probable value. However, it is also true that guaranteeing, in an adequate way, demand for a certain volume of water to effectively satisfy a specific need, entails to evaluate users request, based on which increase or decrease in volumes is defined, which, of course, modifies discharge circulating in channel network and, consequently, the adjustments that operator must make in hydraulic control structures to prevent failing system. Other factors that must be taken into account to minimize the risk of supply failure involve determining those volumes that are lost between supply source and irrigation zone due to aspects such as leaks, seepage or reduction of hydraulic section due to sedimentation and incrustation of solid particles [67,68]. In light of this, findings reported here need to be improved by further investigation of prevailing conditions in order to interpret more precisely how important it was to make efficient use of water resources, especially in times of shortage.

4. Conclusions

Eight ancient aqueducts built in the eighteenth and nineteenth centuries were tested using modern irrigation engineering methods to estimate flow rate through them and to infer their management at plot level as well as their probable yields according to climatological conditions and crops at the different locations under analysis. Regarding hydraulic evaluation using principles that govern free surface flow, findings generally indicate an engineering knowledge quite close to a design that would currently guide a hydraulic section sized to convey similar discharges. Moreover, it was also possible to show that, in each case, the hydraulic section was constructed in a way that its capacity would allow satisfying the water requirements of crops corresponding to each aqueduct. Given such manifestations, it is possible to argue that, during colonial times and independent Mexico, there were already engineering criteria (perhaps as technical recipes) for the design and operation of agricultural hydraulic systems using methods of conduction and distribution by open channels and ditches, and surface irrigation schemes for farming fields.

Despite not having sufficient documentary evidence regarding hydraulics technology, it is not unreasonable to infer that water problems were (the same as they are today) an adverse factor for inhabitants' subsistence within this geographic area and, therefore, a permanent incentive to build structures with an aim to profit available water resources. Somehow, a water shortage allowed Spaniards to put into practice whatever knowledge they had about Roman aqueducts. Thus, the main findings reveal a transmission of knowledge between the Roman culture and the natives of pre-Hispanic Aridoamerica through the Spanish colonizers as far as hydraulic engineering is concerned.

This study is derived from current criteria for operating a distribution and conveyance network that transports a maximum flow rate to meet irrigation area water needs. However, a further in-depth appraisal requires careful attention to other factors involved in local manual operation. Thus, a better understanding of the criteria for design and operation of a network of channels to convey water to an irrigated area during Colonial times and the beginnings of independent Mexico based on hydraulic systems from the Roman civilization; although it is essential to keep on investigating about hydraulic control criteria that may have prevailed at that time, thereby, gaining a better understanding of what importance was given to rational water use.

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