

Original Article

The Hydraulic Engineering of Tipón: A Systematic Review of its Impact and Enduring Legacy

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Abstract - In the southeastern part of Cusco, Peru, the archeological site of Tipón is characterized by its hydraulic system, which is a combination of agricultural functionality and symbolism relying on sophisticated engineering practices. The site includes canals, fountains, and aqueducts, forming a network that seeks precision and beauty. Although it has a high importance and is a source of knowledge, few studies have reported how the hydraulic system works and its implications for the current water sustainability practices. A systematic review using the PRISMA guidelines. It is shown that the interconnected hydraulic system is effective for water distribution, and its applications range from agricultural to erosion control and ceremonial use. The present study remarks the role of the Tipón as a source of knowledge for addressing contemporary problems related to water management, especially in areas under water stress.

Keywords - Inca hydraulic engineering, Tipón, Sustainable water management, Aqueducts, Canals.

1. Introduction

Tipón is an Inca archaeological site located 27 kilometres southeast of Cusco, Peru, which is renowned for its remarkable water distribution system and sophisticated hydraulic engineering. This complex of agricultural terraces, canals, and fountains is considered by many to be a marvel that demonstrates the Incas' profound knowledge of water [1]. The Tipón archaeological site consists of thirteen terraces built in a staircase pattern, supported by well-crafted stone walls and filled with fertile soil. The agricultural terraces are connected by canals that distribute water from springs and rainfall [2, 3]. The system comprises a main aqueduct that branches off into surface and underground canals, allowing water flows to be regulated. Within the hydraulic complex observed, there is a main fountain which, due to its location and capacity, would have served as a reserve in times of scarcity. Its design suggests that, in the face of variations in the flow, it was able to retain water and distribute it in a controlled manner. Channels carved in stone were incorporated at the base of the terraces, the function of which was to capture the surplus and channel it to lateral structures arranged in a descending sequence. This configuration of the Tipón hydraulic complex permits regulating the flow, minimizing soil loss, and conserving the resource efficiently [4, 5]. On the other hand, it is a ceremonial center where Yaku (water) is worshipped [6].

The accuracy and aesthetics of Tipón's hydraulic system represent not only its functionality but also the symbolic and ritual importance of water in the Inca world. Thus, the waterfalls and fountains not only had a practical function but also embellished the landscape and probably had a ritual significance [7]. In accordance with this tradition, today's aqueducts are hydraulic structures that transport a resource from its place of origin to the urban environment, an essential factor in the management and distribution of the resource [8]. Elevated aqueducts allow water to flow between different valleys, depressions, and roads, their ancient construction being dependent on the structural theory of bridges, albeit on a rather smaller scale [9]. Today, they are integrated into more complex systems that include inverted siphons, pumping stations, and conduits, adapting to diverse terrains. Their ability to cross rivers, canyons, and roads makes them key elements in conservation, flood mitigation, and flow diversion projects [10].

Within the water conveyance systems, the canals play an essential role as the main routes for the movement of the water that goes through them. Their effectiveness is enhanced by complementary elements such as weirs, culverts, and bridges, which maintain a stable and regulated flow in different sections of the route [11]. In the scenario of steeply sloping areas, the use of agricultural terraces has proven to be



an effective strategy to conserve not only the soil, but also to regulate the water behavior. Moreover, their specific arrangement allows the retention of moisture in the substrate, and it also allows the runoff to lose strength before reaching critical levels. Nonetheless, in certain cases, specific conditions can arise and favour the soil instability [12]. It is also important to mention that some previous studies have approached these hydraulic solutions from a wide range of perspectives, and in these contexts, they explored not only the functionality of these water solutions but also the cultural and technical implications of their implementation. For example, the research in [6] focused on analyzing how this infrastructure contributed to the sustainability of agricultural production. These varied previous perspectives allowed us to assess the technical legacy of Tipón in the area of development of current water management strategies.

This paper focuses on examining in depth the hydraulic system that was developed at the archaeological site called Tipón. To attain this objective, this research looks in detail at the structural components of the hydraulic system in Tipón, the construction techniques employed in it, and the different implications it had in the agricultural and cultural spheres within the Inca society. The main objective is to gain a better understanding of how this ancient infrastructure has endured over time and what contributions it can offer to modern engineering. In addition, historical sources were reviewed along with contemporary studies that permitted us to establish links between the past and the present.

2. Methodology

The literature review will consider studies, ranging from 2003 to 2024, both in English and Spanish. The current review follows the Preferred Reporting Items for Systematic

Review and Meta-Analysis (PRISMA) statement. The statement is used to facilitate a transparent and complete report for systematic reviews [13].

The Scopus database is used, as it provides a base exclusion for finding relevant studies [14]. Likewise, the Web of Science database is also used [15]. The process began with the identification of keywords.

The search was conducted using combinations of keywords. For SCOPUS, these were I ('Inca' AND 'agricultural systems'), II ('Inca' AND 'hydraulic systems'), III ('Tipón'), IV ('Tipón' AND 'civil engineering'), and V ('Tipón' AND 'hydraulic engineering').

2.1. Identification

Initially, 34 articles were identified by searching for keywords in specialised databases. Additionally, three articles were incorporated using the snowball technique, considering sources such as Google Scholar and other relevant studies, reaching a total of 37 articles in the identification phase.

2.2. Eligibility and Exclusion

In the eligibility phase, 12 duplicate articles were eliminated. Then, after reviewing titles and abstracts, 15 articles were excluded for not addressing the construction aspects of Tipón and its hydraulic engineering, leaving 10 articles. Finally, in the selection phase, after a detailed analysis of the content, one article was discarded for not meeting the defined criteria, resulting in a total of nine articles included in the study. This process is summarized in Figure 1.

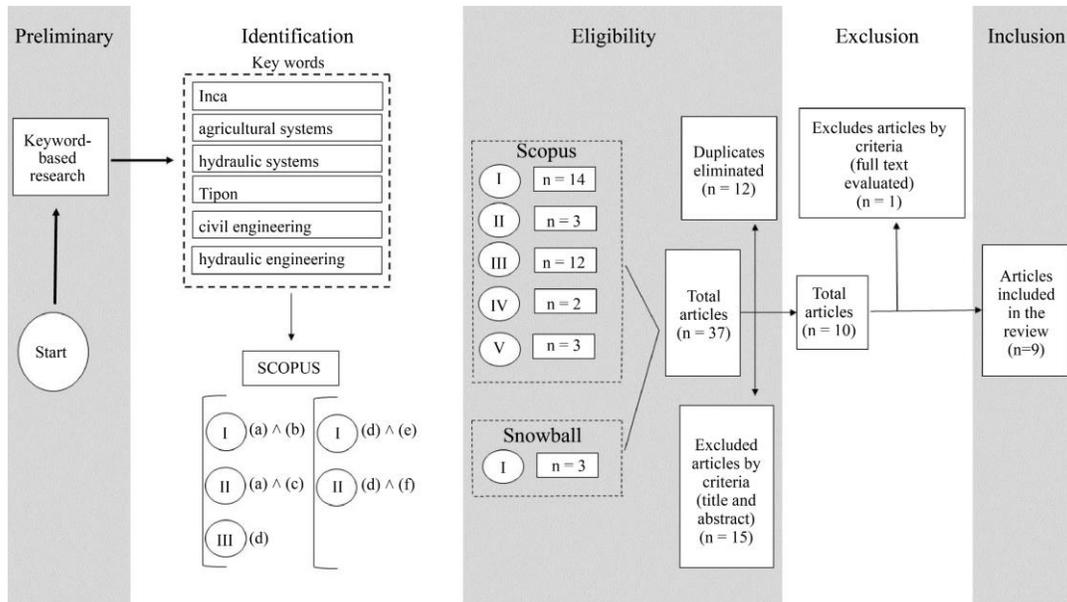


Fig. 1 PRISMA flow diagram illustrating the study selection process

3. Results

The Tipón Archaeological Park, one of the remarkable hydraulic works of the Incas, has been the subject of little research over time. As shown in Figure 2, the number of publications on the site has been limited and sporadic, with a recent increase in recent years. This trend suggests a renewed interest in the study of Tipón, although there is still a wide field to explore.

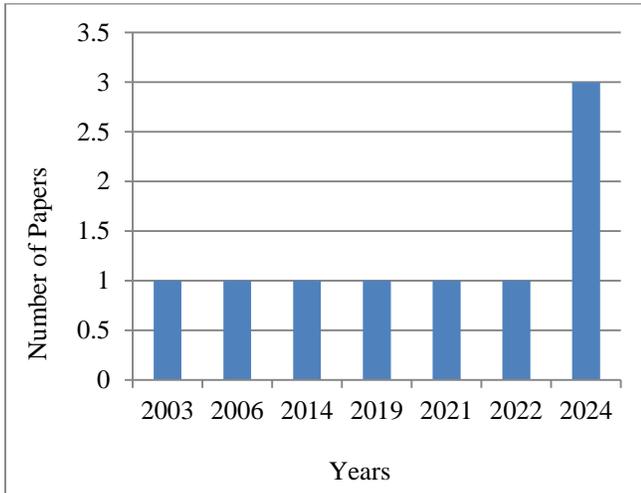


Fig. 2 Distribution of the included studies on Tipón by year of publication

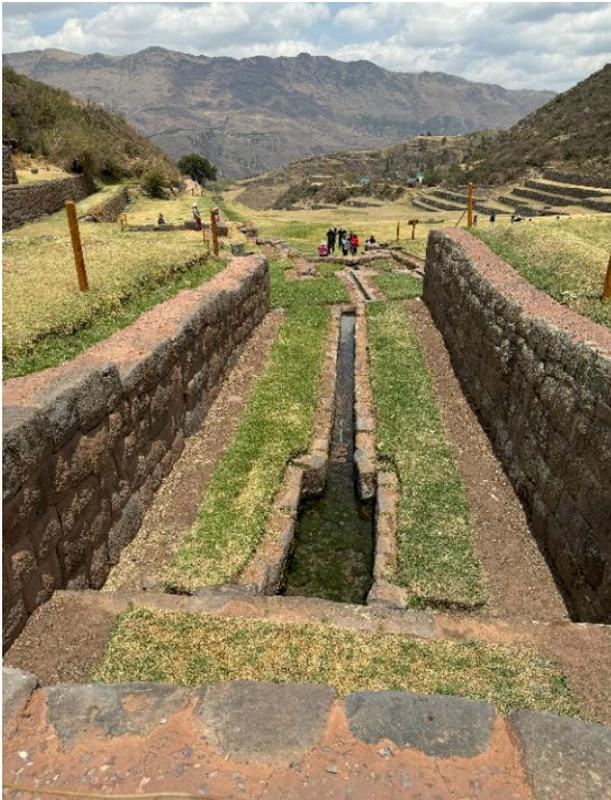


Fig. 3 The main water channel at Tipón, showcasing the precision of Inca hydraulic engineering and stonework

3.1. Analysis of Tipón's Inca, Hydraulic, and Civil Engineering

The Tipón Archaeological Park, as shown in Figure 3, is considered to be a masterpiece of Inca engineering because it stands out for the complexity of its hydraulic system [16]. Several studies have highlighted the precision achieved by the Incas in their designs, specifically the canals and terraces, in order to improve irrigation and prevent erosion [1]. In addition, previous researchers who used computational fluid dynamics have revealed the use of specific contraction devices in the channels that stabilize the flow and improve the hydraulic system [17]. However, despite the historical and technological significance of Tipón, there has been little research on this archaeological park, and this circumstance highlights the need for further study of this area.

3.2. Analysis of Tipón as a Water Shrine

Tipón, the Incan archaeological site, apparently has several functions, like fulfilling functions linked to irrigation and water control, or it even seems to have been conceived with an intention that transcends the utilitarian one. Various explorations suggest that water was more than a simple managed resource; water was understood as an entity with symbolic value within Inca cosmology. The presence of these systems in stepped fountains and the carefully designed waterfalls, along with other structures integrated into the architectural environment, points to a ritual that consisted of reading the flow of water, which is possibly associated with notions of fertility, renewal, and a link with the divinity [18, 19]. The precision by which the channeled water is not only redirected, but also poured at key points in the system, depicts an advanced technical knowledge for those who are familiar with it, and it also portrays an aesthetic search that is similar to other ceremonial spaces such as Tambomachay or Ollantaytambo [17]. The existence of determined areas specifically devoted to the observation of water in movement further reinforces the hypothesis that Tipón could have been employed as a place of pilgrimage or even as a stage for practices that were linked to the Andean cosmovision [1].

3.3. Sustainable Water Management

The fact that a hydraulic system was developed in this type of Andean context reveals a very precise understanding of the environment that surrounded this community at that time, and it also portrays a remarkable capacity to adapt the management of water to variable conditions. In addition, the mixture of natural springs along with river streams offered a stable supply of water, even during periods of scarcity or heavy rainfall [17]. For the purpose of adjusting the flow and avoiding losses in the water circulation system, a good number of reservoirs and spillways were incorporated in a set of strategic points that allowed the regulation of the flow according to the agricultural and ritual requirements [16]. Beyond the more than evident productive function of the terraces, they played a pivotal role in water regulation because these terraces allowed for: retaining the moisture,

reducing the runoff, and even favoring the soil conservation in areas with the characteristic of having steep slopes [18]. This integration between agricultural infrastructure and water management strongly suggests that Inca knowledge was not limited to solving immediate needs, but it likewise incorporated other principles that even today are considered to be essential when studying the treatment of watersheds and the design of resilient strategies in the context of environmental pressure.

3.4. Aqueducts, Canals, and Terraces

The Tipón hydraulic network, made up of canals, aqueducts and reservoirs, represents a remarkable example of the Inca technical mastery in water management, with carefully traced slopes between 1% and 3% that allowed a constant flow without causing erosion [18]; to regulate the flow with greater precision, bifurcations and geometric

variations were incorporated in the traces, applying principles that are now recognized in modern hydraulics [17]; this network did not operate in isolation, since the connection between underground and surface conduits, together with reservoirs located at key points, allowed a balanced distribution of water to the agricultural terraces and other areas of the complex [1]; in addition, the use of floodgates and spillways in stepped canals fulfilled an essential function by modulating the flow, avoiding overflows and conserving the resource without unnecessary losses [19]; Taken together, the constructive precision and integration with the natural environment show that the Incas not only designed functional infrastructure, but also managed to harmonize it with the landscape; Figure 4(a) shows an aqueduct, Figure 4(b) a surface canal, and Figure 4(c) terraces created during the Inca period, all forming part of the system described.



Fig. 4 Key components of Tipón's hydraulic system, (a) A fountain outlet demonstrating precise Inca stonework, (b) A primary water channel running alongside the terraces, and (c) The stepped agricultural terraces that integrate with the water management system.

3.5. Construction Materials of Tipón

The construction of the archeological Tipón site involved the usage of different materials that reflect the precision and the technical knowledge the Incas had in the building of hydraulic and agricultural infrastructures. One of the materials employed in the construction of canals, terraces, and fountains was the pink andesite stone, which was highly sophisticated to use, especially in its careful cutting stage and its assembly without mortar in order to provide structural integrity [18]. This type of assembly not only guaranteed its durability in terms of erosion and climate, but also allowed an efficient water control with very limited leaks and spills [17]. In addition to stone, layers of gravel and soil were present on the agricultural terraces to facilitate drainage and to promote infiltration; water was able to permeate into the soil to provide sufficient moisture for crops without causing any waterlogging (Tipón: Masterpiece of Hydraulic Engineering of the Inca Empire). The combination of materials and construction techniques has allowed the Tipón hydraulic system to function in the present day and demonstrates the ingenuity of the Incas and their ability to

meld infrastructure with their prevailing natural environment [19].

3.6. Residence of Inca Royalty

Not only was Tipón a hydraulic and agricultural centre, but it was also a home to the Inca elite who had some important connection to the Inca Wiracocha. The quality of its architecture and the nature of its designs suggest that it was not a place meant for common people, but for the Inca nobility [19]. Because the structures were at once formal and functional, it seems likely that Tipón served not only as a place to rest but also served an administrative role, an agency of Kontrolle over agricultural and water resource management [18]. The presence of fountains and ceremonial areas reinforces the idea that the site had an exclusive use, where water was not only used for agricultural production, but was also part of the symbolism of power and connection with the divine [1].

Figures 5(a) and 5(b) show much of the structure of the Tipón archaeological park.



(a)



(b)

Fig. 5 Panoramic views of the Tipón archaeological park, (a) A wide perspective of the main terrace complex and water channels, and (b) A detailed view of the massive, finely constructed retaining walls.

4. Discussions

The hydraulic system located in the archeological site called Tipón combines aqueducts, canals, and terraces designed to harness water and reduce soil erosion [5]. The limited documentation of this archaeological site is a limitation for the incorporation of this architecture into new current solutions that could benefit areas with high water vulnerability. Although academic interest has grown in recent years, the number of studies remains limited [2], reinforcing

the need for further research into these techniques as part of a structural response to the water crisis.

The Inca society managed to regulate water flow through surface and underground canals, allowing the storage and distribution of water even under adverse weather conditions [7]. Despite the proven effectiveness of this system, the principles underlying it are rarely applied in contemporary engineering, highlighting a gap between ancestral knowledge

and modern solutions. Recent research on the mentioned archaeological site that studies fluid dynamics has identified the use of specific contractions in the canals, which improves the hydraulic efficiency [17]. This recent study on the Tipón is a technical example of how previous technologies could be used, in this case, for an application in the optimization of water distribution in arid regions.

It is worth mentioning that the Inca society's hydraulic systems are based on those of other societies, like the Chimú. The Inca conquest of the Chimú around AD 1470 followed an overlap between the two societies. Aiming to increase food production, the Inca incorporated the existing Chimú canal networks and, using their engineering knowledge, designed and created standardized, segmented field systems [20].

The standardization, segmentation, recursive fields in a grid pattern, and served by lateral canals helped to minimize water wasted, which was essential in agriculturally marginal areas. There is a sequential development infrastructure regarding the irrigation systems. Before the Chimú, the Moche society built up a canal infrastructure. This can be evidenced in the Jequetepeque valley, where numerous Moche settlements, roads, and irrigation canals were documented [21].

The lack of systematic review studies on hydraulic architectures used by the Inca society has limited their incorporation into contemporary water management approaches. This is indeed not due to a lack of technical value, but rather due to operational translations that allow their principles to be adapted to current contexts. This refers to understanding principles and design logics that have been historically proven to be effective and can be applied, especially in territories where conventional modern solutions have shown limitations.

5. Conclusion

Observing the Tipón hydraulic system allows us to have a deeper appreciation of the degree of sophistication achieved by the Incas with regard to water management. The great number and diverse interconnections among terraces, canals, and fountains are evidence that these infrastructures do not respond solely to a functional logic, but rather reveal a deep understanding of their environment and their capacity to adapt that transcends the purely technical aspects.

Each of the different components seems to have been conceived not only to fulfill a unique task, but rather to be integrated into a whole structure that interacts with the terrain, the climate, and the needs of the community.

Although Tipón's hydraulic system stands out for its functionality and resistance, its configuration also reveals a symbolic dimension linked to water, perceived not only as a physical resource, but as a component with ritual implications within Andean thought; the way in which channels and sources are distributed suggests that the flow of the liquid obeyed a logic that intertwined practical utility with cultural meanings, in a scheme where the technical was not detached from the spiritual; this reading broadens the scope of design and allows it to be understood as part of a more complex vision of the territory; in the present, marked by environmental tensions and water scarcity, taking up certain principles observed in Tipón could offer alternatives to design hydraulic systems that better respond to the conditions of the environment; It is not a question of reproducing old schemes, but to identify elements that, when reinterpreted with criteria, can complement current approaches; the interaction between traditional knowledge and modern developments has the potential to strengthen water management strategies where conventional solutions have shown limitations.

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