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Integrating pre-Hispanic human legacy in central Mexico to move toward adaptive land and water management

Fernando Jaramillo Monroy[1], Elisabet V. Wehncke[2*], José Luis Rodríguez de Gante[3], Víctor Hugo Flores-Armillas[4] and Oscar Pohle Morales[5]

ABSTRACT

Culturally integrated approaches to water use and management are critical for achieving IWRM commitments and sustainable development goals. Over millennia, ancient civilizations in Mesoamerica developed sophisticated hydro-agricultural systems by channeling water from natural sources to sustain crop cultivation. Morelos state, Mexico, has a cultural, archeological, and historical heritage related to land and water control through the use of *apantli* networks (irrigation channels). However, their current state of deterioration illustrates how ancestral values have been forgotten over time. In recent decades, Morelos has suffered environmental degradation as a result of high population growth and unplanned urban, agricultural, and industrial development. This study explores how archaeological heritage can support the preservation of cultural ecosystem (CES) services linked to the *apantli* network in the state of Morelos. It presents the main findings of restoration efforts, surveys, characterization and socio-historical analysis carried out in Cuernavaca and Jiutepec, highlighting the ecological importance of the network and the challenges facing its sustainable management. It is anticipated that the recovery of the pre-Hispanic *apantli* network in Morelos will not only contribute to improved water and land management, but will also help to revalue the historical interactions between people and nature, thereby supporting ongoing efforts in conservation and ecological restoration.

Keywords: Historical heritage; Cultural landscapes; Water management.

1 Comisión Estatal de Biodiversidad de Morelos, Privada Manantiales S/N Colonia Chapultepec, Cuernavaca, Morelos, México C.P. 62450.

2 Centro de Investigación en Biodiversidad y Conservación, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col. Chamilpa, 62209 Cuernavaca, Morelos, México. Present Address: Vda. El Hato, sector 5B, Finca Buenos Aires, La Calera, Cundinamarca, Colombia.

3 Consejo de Cronistas de Jiutepec, Morelos, Mexico. 4 Centro de Investigaciones Biológicas, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col. Chamilpa, 62209 Cuernavaca, Morelos, México.

5 CIESAS Golfo-CONAHCYT.

* Corresponding author ✉. E-mail address: EVW (lizwehncke@gmail.com), FJM (ferjarmor@gmail.com), JLRdeG (turismo1jiutepec@hotmail.com), VHF-A (victor.flores@uaem.mx), OP (opohle@gmail.com).

SIGNIFICANCE STATEMENT

Traditional water management practices, such as the *apantles/apantli* irrigation canals, have long been integral to Mesoamerican culture, particularly in the Cuauhnáhuac Valley of Morelos, Mexico. Despite their historical and environmental significance, these systems face decline due to limited recognition in modern decision-making, risking their cultural and ecological value. This study frames *apantles* as a Cultural Ecosystem Service (CES) under the Nature's Contribution to People (NCP) approach, which emphasizes diverse, culturally embedded benefits co-produced with nature. By highlighting the role of *apantles* in preserving hydrological balance and environmental integrity, the study advocates for their protection and sustainable management, warning against developments that threaten this irreplaceable heritage.

INTRODUCTION

The overexploitation of natural resources and the increasing frequency and intensity of extreme weather events have resulted in biodiversity loss and inequality in the provision of ecosystem services; together, these factors pose serious threats to the survival and well-being of all human and non-human beings. This global scenario threatens our reciprocal and dynamic relationships with nature (including how we value nature) and poses immediate challenges in terms of our commitment to keeping and protecting such relationships (Chan et al. 2012a,b; Chan and Satterfield 2016; López de la Lama et al. 2020; Plieninger et al. 2014).

The Ecosystem Services (ES) concept which emerged in the late 1990s (Costanza et al. 1997; Daily 1997) as a strategy to 'internalize' the value of ecosystems and convey it to broader audiences, was officially consolidated by the Millennium Ecosystem Assessment program (MA 2003, 2005). Since the term "ES" was coined, the most common ES categorization schemes (Haines-Young and Postchin 2018; MA 2005; TEEB 2010) have included 'non-material' benefits that people obtain from ecosystems, such as esthetic information, recreation, spiritual enrichment or cultural heritage (MA 2005). However, these so-called Cultural Ecosystem Services (CES), have received less methodological development, historical analysis, and competencies than other more tangible ecosystem services (Chan et al. 2012a,b; Daniel et al. 2012; Hernández-Morcillo et al. 2013; Hirons et al. 2016; Plieninger et al. 2013; Schaich et al. 2010). Perhaps the most worrisome effect of this is that traditional knowledge has been frequently underutilized in decision-making about landscape and ecosystem management, which threatens the loss of heritage values and cultural landscapes (Wu and Petriello 2011).

Several scientific discussions and reviews have specifically focused on how cultural heritage can be conceptualized within the field of ES (Hirons et al. 2016; Hølleland et al. 2017; Kirchhoff 2019; Sánchez et al. 2020; Milcu et al. 2013). These studies have made it clear that there is still a lack of consensus on techniques that are not being produced in the field of ES (Hølleland et al. 2017). After the European Landscape Convention (UNESCO 2013, 2018), the idea of heritage was broadened to include a spatial approach and territorial perspective by considering landscapes to be heritage realities resulting from the interaction of humans and natural factors. Currently, the exploration of possible links between culture and development has led the discussion to a much more flexible interpretation that focuses on the role that heritage currently plays for citizenship (Loulanski 2006; Mrak 2013). In referring to Cultural Landscapes (CL), CES offers a methodological framework from which to explore the role of this heritage reality as a social resource by detecting which features make it useful and beneficial for people from a cultural point of view (Assandri et al. 2018).

Human cultures, knowledge systems, religions, heritage values, and social interactions are affected and shaped by nature; at the same time, people have the potential to modify and influence the environment to obtain the most valued services according to their perceptions at a given moment. Culture—the set of knowledge, ways of life, forms of organization, and traditions of a community (Leiva et al. 2019)-has the potential to maintain or to change the state of ecosystems by being manipulated and transformed for the community benefit (Balvanera et al. 2010). Culture includes traditions that recount what has worked in the past and what people have learned from their environment (Tengberg et al. 2012). Beginning mainly in the 21st century after the World Heritage Convention (Jokilehto and Cameron 2008), the idea of heritage as a single historical object has been overtaken by a broader spatial approach through concepts such as ambience, context, site and landscape. Thus, Tengberg and collaborators (2012) suggested that cultural heritage be defined as both tangible and intangible heritage within the landscape that helps to maintain meaning and a sense of collective identity, emphasizing the intimate linkage between cultural heritage and identity (features within landscapes that are significant in some way to the present). Thus, it is necessary to recognize that tradition is subject to changes imposed by the environment and life itself (Villagómez-Reséndiz 2020).

The relationships between humans and nature are complex and deeply intertwined, to the extent that they are often inseparable. In many cases, defining nature requires acknowledging the presence and influence of human elements (Russell et al. 2013). Most previous studies conceptualized nature as the primary source of benefits to humans, often neglecting the integral role of human activities and other forms of anthropogenic capital in the co-production of such benefits (Kachler et al. 2023). Recent literature highlights that Nature's Contributions to People (NCP) are not inherently nature-derived, but rather predominantly result from the co-production processes involving both natural systems and various forms of anthropogenic capital (Cook et al. 2020; Hill et al. 2021; Lavorel et al. 2020). We understand co-production as the joint contribution of natural and anthropogenic capitals that generates material, regulating, and non-material NCP (Díaz et al. 2015). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) conceptual framework on Nature's Contributions to People (NCP) emphasizes the interactions between humans and nature, and highlights the key role of anthropogenic capital—such as knowledge, technology, and institutions—in shaping how nature's benefits are produced and delivered to people (Hill et al. 2021; Kadykalo et al. 2019). Thus, IPBES established to conduct assessments at global and regional levels, has adopted a Conceptual Framework to guide its reporting and communication activities (Pascual et al. 2017). This framework conceptualizes the interactions between humans and the rest of the living world through six interrelated components: (1) nature, encompassing biodiversity as well as elements of biocultural diversity; (2) anthropogenic assets, such as education, health, technology, and finance; (3) institutions, governance systems, and other indirect drivers of change, including social norms, rules, and broader socioeconomic, cultural, and demographic factors; (4) direct drivers of change in nature, both human-induced and non-human; (5) nature's contributions to people (NCP), defined as the full range of benefits and detriments that arise from human–nature relationships; and (6) a good quality of life, understood as a multidimensional concept shaped by diverse cultural and societal contexts (Pascual et al. 2017).

According to Hill et al. (2021), Kachler et al. (2023), and Pascual et al. (2017), material NCP refer to all material contributions (i.e. products, substances, or material elements) directly nourishing or supporting people. *Regulating NCP* refer to environmental processes and functions contributing to human well-being, for example, through pollination and hazard mitigation. *Non-material NCP* refer to people's subjective or psychological experience of nature, both individually and collectively, for example, by getting inspired by nature (Bhattacharjee et al. 2022; Díaz et al. 2018). *Anthropogenic capitals*, also termed anthropogenic assets (Palomo et al. 2016), refer to "built infrastructure, health facilities, knowledge (including [indigenous and local knowledge systems], and technical or scientific knowledge, as well as formal and non-formal education), technology (both physical objects and procedures), and financial assets among others" (Díaz et al. 2015). However, the wide spectrum of values through which people attribute meaning and importance to NCP is rarely recognized or explicitly taken into account in decision making. It is essential for planners to consider the temporal dynamics of the relationship between anthropogenic capital inputs and the provision of NCPs. Better understanding and recognition of the suite of values associated with NCP is thus crucial in sustainability science (Pascual et al. 2017). In the state of Morelos, Mexico, it is possible to follow the story that goes from pre-Hispanic hydraulic engineering to the sharp dichotomy that currently exists between ancestral knowledge and contemporary imposed techno-scientific knowledge. Although technological and scientific knowledge can promote innovation, their imposition can generate conflicts and contradictions that result in apathy and, ultimately, forgetting of what was once a holistic regional vision regarding the functioning of a socio-hydrological system. Before the arrival of the Spanish, the region settled in small villages in Nahua culture (Rabiela et al. 2009). Although there were exchanges with other ethnic groups that settled in the region, Nahua culture remained predominant during the first half of the 20th century (Benítez 2022). After the state of Morelos became a federal entity, it continued to manifest its cultural heritage under the strong influence of the inherited Nahua cosmovision (Benítez 2022). However, domination of Hispanic contact first and later of the national state led the communities to appropriate new and diverse cultural aspects that influenced their perceptions of the world (Benítez 2022).

In pre-Hispanic Mexico, knowledge of nature and practical experience in the management and control of water-generated techniques and hydraulic works served as the foundation for the development of agricultural irrigation, the construction of water supply systems for the population, and the construction of drainage infrastructure, among other applications (Rabiela et al. 2009). Irrigation is a fundamental characteristic of Mesoamerican culture. The lands of the state of Morelos have been the site of broad development of water control and collection systems since ancient times, as well as irrigation from perennial springs that originate in the state's mountains and volcanic and alluvial valleys. The subtropical climate, sufficient rainfall regime, and absence of frost in most of the study area allowed the intensive cultivation of many crops, including cotton, corn, chili, squash, chilacayote, beans, chia, sweet potato, jicama, avocado, tomatoes, and fruit (Rabiela et al. 2009). Morelos was the location of the first sugar cane plantations in New Spain, established by Hernan Cortés in 1540, who initiated a series of hydraulic works. The irrigated lands and hydraulic resources of this and other rich valleys soon passed into the hands of the conquistadores, who attempted to cultivate new crops on the land through legal means (agreements with the indigenous nobility, royal grants or purchases) or usurpation.

Currently, the northwestern region of Morelos is recognized for its beautiful natural landscapes and striking ravines. The region has a wide array of ecosystems that provide a wealth of ecosystem services, including abundant surface water and groundwater, the generation of fertile soils and microclimates, and the maintenance of comfortable environments. However, natural wealth has experienced accelerated deterioration and destruction in recent decades because of explosive increases in the human population and urban, agricultural, and industrial development. At the same time, there has been a lack of public institutions' planning and sustainable management of water, territory, and natural resources.

In an effort to promote the protection and sustainable management of the traditional irrigation canal system, known as *apantles or apantli*—and to prevent urban development and water users from adversely affecting this natural and cultural heritage, which plays a vital role in maintaining the environmental and hydrological balance in the southeastern region of Morelos, Mexico— this study presents the results of efforts aimed at its restoration, particularly in the municipalities of Cuernavaca and Jiutepec. We expect that the recovery of the pre-Hispanic network of the *apantli* system in the state of Morelos will not only benefit the current management of water and territory, but will also revalue the dynamics that existed between people and nature, by supporting efforts to conserve and restore nature. This aligns with the NCP concept as a transdisciplinary, action-oriented, and inclusive approach that embraces plural perspectives. It offers a framework for advancing understanding of how rapid changes in nature impact quality of life across societies and socio-ecological systems.

This work also revisits and further elaborates on aspects of a previously published study (Jaramillo Monroy et al. 2021), examining the historical evolution of socio-ecosystems and the patterns of land and natural resource use within a small watershed in the Morelos region. This study combined sociohistorical and functional analyses from a regional perspective to identify weaknesses, solutions, and alternatives and understand land and water management patterns. One of the main challenges of that study was to promote the development of citizen institutions with the greatest possible autonomy, in charge of managing the environment and natural resources by incorporating the legacy of ancestral water management (in Morelos in general, and specifically in the city of Cuernavaca). These institutions would guarantee technical and scientific capacity, citizen participation, and the continuity of programs and projects in the medium and long term (García-Barrios et al. 2008, 2015).

As a starting point and to understand the dynamics of water, territory and the peoples of this region, this time, the objective of this study is: 1. to provide a brief overview of the perception and relationship between the ancestral communities of Morelos and the territory, particularly water management and the construction of *apantli*. In the most literal sense, *apantli* refer to furrows in the land that were constructed to irrigate crops; but beyond the constructions themselves, they denote the existence of organized and systematized hydraulic knowledge that was constantly conserved, transmitted, and renewed (Rabiela et al. 2009); 2. to summarize how the irrigation system of the Valley of Cuauhnáhuac (i.e., Cuernavaca) evolved to its current state with the intention to understand how the Nahua worldview (and its manifestations in daily life, rituals and beliefs) permitted continuity in Morelos despite the miscegenation and imposition of the Western culture from the Mexican State in the 19th century and in the years following the 1910 Mexican Revolution; and 3. to conduct an inventory, characterization, and to map the *apantli* system that feeds the Chapultepec Spring. We expect this will allow the competent authorities and system concessionaires to seek its protection and sustainable management, as well as to incorporate the NCP concept in order to prevent urban development and water users from negatively impacting this natural and cultural heritage in Morelos.

MATERIAL AND METHODS

Data analysis protocol

Using the approaches of historical ecology, environmental history and landscape archaeology (Moreno and Montanari 2008), and based on results from a doctoral thesis on this topic (Jaramillo Monroy 2021), here we offer a review based on bibliographic and documentary information to summarize the conception of territory and water by the ancestral populations of Mesoamerica.

The uses and management of water and territory in the Cuernavaca Valley: We provide a brief overview of the evolution of land and water use and management by the various communities that inhabited the study area to the present, that was analyzed in Jaramillo Monroy et al. (2021). Information was taken from historical documents and archives consulted at the National Archives of Mexico; and from documents that particularly comprise the public and citizen management strategies for the El Pantano micro-basin, which are available from the 1960s to the present (Aguilar Benitez 1995; Ávila Sánchez 2001; Ceccon and Flores Rojas 2012; Flores-Armillas 2016; Sánchez Resendiz 2006) and contain information about government and citizen actions and experiences related to the valuation, planning, use, and management of land, and to the protection of the environment, biodiversity, water, and other natural elements.

Geohydrological aspects of the study region (El Pantano micro-basin): To identify the possible causes that have led to the current problems related to water and territory in Morelos, we present the main results of a biophysical study (Jaramillo Monroy 2021), based on hydrological, geological and climatic information obtained from Pohle Morales (2016), that help us understand the hydrological functioning of the El Pantano micro-basin system. The selection of this micro-basin is due to the fact that the main human settlements in Morelos were located in its southern part and, in addition, it is where archaeological elements related to the cult of water were found (Smith 2018).

The interrelationships between natural and social components and the causes of conflicts in watershed management, were summarized from systematized information that used flowcharts of a dissipative, open, and self-regulating system, using as a model the one proposed by Oswald Spring and Hernández Rodríguez (2005). These methodologies allow to identify potential imbalances (tensions, conflicts, and ruptures) in the system and subsystems as a whole, and to highlight virtuous circles that could reinforce sustainable processes that generate greater equity. For more precise information on this see, Jaramillo Monroy et al. (2021).

The apantli irrigation system of Cuernavaca and Jiutepec: Between 2015 and 2016, Pohle and Jaramillo conducted their first survey of the *apantli* network at 70 control points and along >30 km of channels derived from the Chapultepec springs. During August and September 2019, several field visits were made to the *apantli* area starting from the origin of the flow in Chapultepec Park, following its trajectory until reaching the sink areas in El Pantano and Joya del Agua micro-basins located in the municipality of Jiutepec.

To characterize the current state of the *apantli* network in Cuernavaca and Jiutepec municipalities, measurements of channels were taken and the type of channel was recorded to establish 152 control points on different sections of the channels (Figure 1). At each control point, characteristics such as the type of construction, measurements, speed, and water quality, as well as the presence of fauna were recorded. The coordinates of each point were taken for cartographic representation.

Thus, a monitoring strategy was designed that included:

1. *Characterization of the apantli*: The canals were classified according to their construction material: earth, cement, stone, mixed combinations (stone-cement-earth), stone casing, pipes, asbestos or concrete pipes, and underground canals. Their physical condition, current functions, and maintenance status were recorded based on direct observation and photographic records.
2. *Structural Measurement*: At each control point, measurements were taken of the channel height, width, and depth to establish average hydraulic profiles.
3. *Registration of control devices*: The presence and location of floodgates and distributors, essential for the distribution of irrigation water, were recorded.
4. *Hydrological flow monitoring*: The route of the canal system was identified, and flow rates at various points were calculated using the basic flow formula, where is the flow rate (m^3/s), the volume of water (m^3), and the filling time (s). This information was compared with historical records provided by local stakeholders with experience in traditional irrigation management.
5. Assessments of water quality were made through direct observation and evidence of trash or chemical contaminants on site and through data collected from interviews with local residents.
6. *Identification of aquatic and riparian fauna*: Systematic observations of visible fauna (fish, aquatic insects, associated birds) were made as biological indicators of water quality, based on regional identification guides.
7. *Georeferencing and generation of thematic cartography*: Each control point was georeferenced using a GPS receiver in UTM coordinates, WGS84 datum, zone 14N. This information was integrated into a Geographic Information System (GIS) using ArqMap 8 software, which allowed the canal network to be mapped and its spatial status characterized.

RESULTS

The Mesoamerican conception of water and territory

The Olmec culture, which flourished from 1200 to 400 B.C. in regions of present-day Tabasco, Veracruz, and Guerrero, is considered the first great civilizational synthesis of the Mesoamerican world and is classified as the mother culture (Martínez-Ruíz and Murillo 2016). The Olmec culture generated a complex symbolic paradigm, a cosmovision structured around water, land, and/or seeds and the power of rulers in

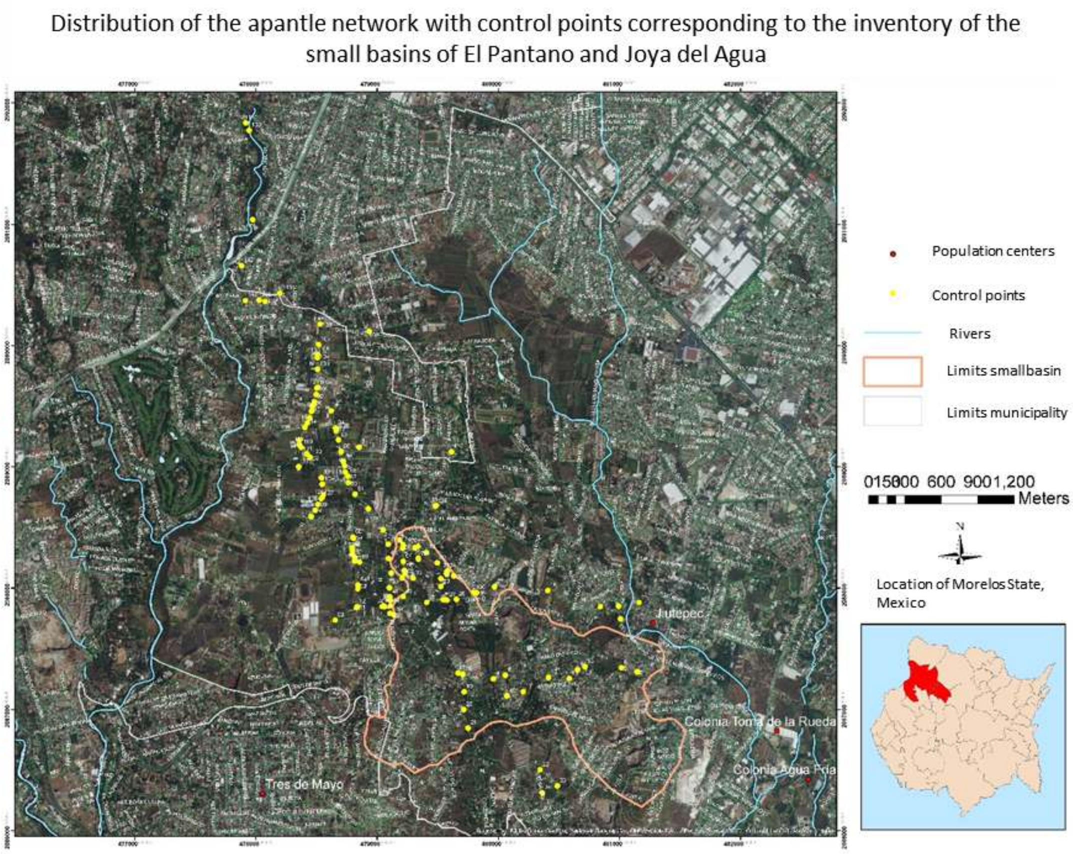

Figure 1. General location of Jiutepec's water channels or *apantli*, as well as the 152 control points in the network system (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the micro-basins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019).

a cult of rainfall, stars, and power. By 'cosmovision' we refer to the structured vision in which the ancient Mesoamericans coherently combined their notions about the environment in which they lived, and about the cosmos in which they located the life of man (Broda 1991, 2012). This model became a matrix of the indigenous worldview that would be replicated secularly in the Mesoamerican region and that during the colonial period would become amalgamated with Christianity, giving rise to an agro-pluvial Catholic religiosity that currently prevails in rural and indigenous communities of Mexico (Martínez-Ruíz and Murillo 2016).

The wealth of knowledge and observations about nature developed by the Mesoamerican peoples is undeniable. In the construction of their worldview and rituals, they mixed exact knowledge with magical beliefs about the existence and personification of meteorological phenomena and geographical features such as hills and valleys, all of which were considered living beings (Broda 2016). In Mesoamerican religious thought, representations of space and geographical features were conceived of as large vessels, like houses or reservoirs, in which groundwater was contained, whose function was to water the fields. The space within that vessel was called '*Tlalocan*', the paradise of the rain god, a place of abundance from which the rivers, lakes, and sea emerge (Broda 2016). The summits of the hills give rise to clouds and mist that also cover the valleys and ravines of rugged landscapes (Broda 2016). Natural phenomena—which simultaneously include the rains necessary for agriculture and the threatening aspects of storms, lightning, frost, and flood-came to be personified in the cult to '*Tlaloc*', the personification of the cult of water and also of the hills for the Mexica culture. Thus, the Mexica god of rain corresponds to the Mayan god '*Chac*', the Zapotec God '*Cocijo*', the Totonac god '*Tajin*', and so on (Broda 2016). Thus, the obsession with rain control, a determining feature of religion, had a material basis in the natural conditions of the landscape and the environment. However, this is also derived from the fact that in Mesoamerica, extreme weather conditions are generally linked to an enormous variety of microclimates that depend on altitude and other regional geographic factors. *Tlaloc* had as consort *Chalchiuhtlicue*, the one with the jade skirt, goddess of terrestrial fresh water from springs and lakes, especially from the Mexico lagoon (both deities were represented in the Borbonic Codex, dressed in luxurious blue paper ornaments). On the other hand, *Huixtocihuatl* was the goddess of salty sea water, and its importance was to be an absolute symbol of fertility (Broda 2008).

Rituals dedicated to the deities of water and corn formed the central nucleus of various Mexica ceremonies. This system, founded on centuries (in some cases, millennia) of tradition, was violently broken during the Spanish Conquest. The rites most closely linked to the life of farmers survived in their connection with the seasonal cycle within a fragmented cultural universe exposed to strong pressures of social, political and ideological changes (Báez-Jorge 1998; Broda 2004, 2009). In indigenous farming communities, abundant knowledge related to observation of the environment and natural cycles, geography, botany, and agriculture has been found. Rural life continues to depend on these local manifestations and their proper management. These practices allowed the reproduction of many elements of cosmovision, which are now seriously threatened by the advancement of modern technology, urban growth, and the destruction of the environment (Broda 2016).

An archeological investigation carried out in 1967, in an area measuring approximately 700 km^2 in the eastern part of the Valley of Mexico, Texcoco (Parsons 2023), revealed the ancient hydraulic system of Tetzcotzingo, a system of aqueducts, canals and terraces that fed the gardens of Nezahualcóyotl, the king of Texcoco. The studies were extended in 1969 and 1975 to other parts of the Valley of Mexico, which formed part of a larger synthesis of pre-Hispanic settlement patterns. Apparently, just as there was a water supply system, there was also a drainage system to cope with extraordinary flood events, which allowed the water to continue its course outside the gardens (Miranda Linares et al. 2023). However, despite the pre-Hispanic importance of hydraulic infrastructure (canals, terraces, paths, baths, sculptures) that carried water over a horizontal distance of more than 10 km to the recreational gardens of the king of Texcoco, the transformations over the past half century (urbanization, agricultural mechanization, land reclamation and reforestation, mining, vandalism, erosion) have inflicted extensive physical deterioration on the ancient remains that are still preserved (Parsons 2023). The same fate seems to have met the channels that supplied water to the agricultural terraces, from an unknown number of permanent springs at the base of the mountain range. Apparently, until 1970, water had been allocated to the rapidly growing urban populations in the area. The huge aqueducts in the area have been damaged by erosion and vandalism and are in precarious condition. Many of the hydraulic resources have been reserved and seized for the noble class of Texcoco, since archeological remains there show the existence of recreational gardens for the ruling elite (Parsons 2023). It has not been easy to date the original construction of these vestiges, but they originated in the Postclassic period with the development of the gardens. The large-scale drainage of the large swamp south of Lake Chalco, Xochimilco, gave rise to the system of *chinampas* (Parsons 2023). Today, the old agricultural terraces on the slopes of Cerro Tetzcotzingo have been used for the construction of weekend houses, and many water resources have been readjusted to non-utilitarian uses, such as private swimming pools.

Historical events around the Cuernavaca valley irrigation system, Morelos

Irrigation and hydraulic works were a technological change that revolutionized pre-Hispanic peoples. It is estimated that the first inhabitants arrived in the state of Morelos around 7,000 years B.C. (Aguilar Benitez 1995), and that agriculture began between 6,000- and 4,000-years B.C. (Corona 2010; Von Mentz 1993). The people who inhabited these lands around the 13th century A.D. called themselves '*Tlahuicas'* and spoke Nahuatl. They constructed furrows to move water to irrigate arable land, which they referred to as *apantli*. Three hundred years of water culture allowed them to manage water in a way that kept it clean and regulated for its distribution among crop fields and other needs of society.

When the *tlahuica* people occupied the Jiutepec (Xiutepec) area around 1100 A.D., the Olmecs had already inhabited this territory (Corona 2010; Villaseñor 2010). Since then, the Jiutepec area and its surrounding region have undergone five main historical periods: the pre-Hispanic period, the colonial period, the independence period, the 20th century, and the present (Jaramillo Monroy et al. 2021). The State of Morelos, in particular, has a pre-Hispanic cultural history of land management and water use, which was originally governed by strict rules regarding equity and care of the resource; these rules are no longer observed (Guzmán Puente 2017). On the other hand, pre-Hispanic codices provide strong evidence of the effective irrigation of the agricultural land of Jiutepec by *apantli* networks before the arrival of the Spanish, as demonstrated by a boom of production of blankets made of cotton (a water-demanding crop) that were paid as tribute to the Triple Alliance (The largest Mesoamerican alliance made up of the lordships of Tlacopan, Texcoco and Tenochtitlan, which joined together in the 15th century, with the aim of imposing their hegemony over the Valley of Mexico against the lordship of Azcapotzalco).

The irrigation system of the Valley of '*Cuauhnáhuac'* (i.e., Cuernavaca) is also known through historical documentation because some of the first sugar cane plantations and sugar mills in New Spain were established there. Sugar cultivation reached Morelos in 1530, modifying the pattern of agricultural exploitation and the orientation of the local economy. Around 1540, Hernán Cortés began a series of hydraulic conduction works, the first of which diverted the Chapultepec Spring from its source through a 1.5-kilometer aqueduct to the fields of Atlacomulco (Barrett 1977). This transformation radically converted pre-Hispanic hydraulic systems and marked the beginning of four centuries of drastic changes in land use and configuration. Industrial sugar production had a strong impact on settlement patterns and agricultural production in the different Morelos regions. On the one hand, the thriving industry required large contingents of labor, which caused large population movements from the northern mountainous areas of the current entity and other nearby places, toward the valleys of Cuernavaca and the Plan de Amilpas area. In addition, this region is an important producer of grains, fruits, and legumes, which are required in both Mexico City and local markets (Rabiela et al. 2009).

The first sugar mills were established on the border between temperate and warm lands, but they were especially developed in the latter due to access to the main surface currents and a highly developed hydraulic system. In addition, the cooler climate to the north required a larger volume of firewood to fuel sugar mills and boilers. This approach was extremely advantageous for new landowners, who practically appropriated the infrastructure built by the pre-Hispanic cultures that inhabited those places (Rabiela et al. 2009). During the colonial era, the *apantli* were replicated on a massive scale using the pre-Hispanic strategy to support the irrigation of thousands of arable hectares of sugar cane. Thus, large haciendas were formed, most of which already existed at the beginning of the independence struggle. The year 1810 found the region in full agricultural development; the war for independence stopped progress but did not destroy the nascent 'latifundismo', the system of great landed estates in Latin America (Rabiela et al. 2009).

Beginning at the end of the 19th century, three elements had a direct impact on the composition and arrangement of the territory: the organization of agroindustrial production around the haciendas and sugar mills; the structure of the transport system (especially the railways, which expedited movement of products from farms to consumption centers); and the emergence of Cuernavaca as an important urban center in the management of commercial, political, and administrative activities, both at the state and federal levels (due to its proximity to Mexico City).

After the revolutionary period, around 1942, most of the irrigated lands were planted with sugar cane and rice. By 1950, the amount of agricultural land in Jiutepec was 4312 ha, of which 30% was irrigated. By 1960, irrigation had decreased to 1193 ha, and by 1970, to 931 ha. By 1975, no sugarcane planting was recorded, and it was replaced by corn and tomato, which occupied the second place in production on a national scale (Jaramillo Monroy 2021). In 1977, ornamental flower cultivation began, linked on one hand to the opening and proximity of urban markets, and on the other to the increasing contamination of water and land that forced the planting of products not intended for human consumption (Jaramillo Monroy et al. 2021).

Geohydrological aspects of the study region

The Northwest Region of the State of Morelos, where El Pantano micro-basin is located, is found in a transition zone between the Trans-Mexican Volcanic Belt and the Sierra Madre del Sur (Fries 1956, 1960; Jaramillo Monroy et al. 2021). The geological evolution of this region has caused a ravine system that strongly influences the climate, biodiversity, and hydrological currents of the region. However, in the last 40 years, Morelos has lost most of its ecosystems (Conafor 2013), ranking second in Mexico in terms of the degree of transformation and destruction of natural ecosystems (Flores Villela and Gerez 1994). Morelos is one of the most densely populated states in the country (INEGI 2017) and has been subject to uncontrolled and unplanned increases in urban and industrial settlements in areas with high soil permeability. This has affected several ecosystem services, such as the maintenance of a hospitable microclimate due to the presence of numerous hot and fresh water springs and natural vegetation (Jaramillo Monroy 2010; Pohle Morales, *personal comment*). Together with the Amacuzac hydrological system, the Pantano micro-basin forms part of the headwaters of the Balsas River hydrological region, providing drinking water and irrigation to almost half of the state (García Barrios et al. 2008) and constituting an important biological and hydrological corridor between natural protected areas and agricultural zones. Thus, its conservation is a priority in the region for the maintenance of numerous ecosystem services (Aguilar Benitez 1995; Batllori Guerrero 2004; Jaramillo Monroy 2010).

Jiutepec's municipality and the El Pantano micro-basin (294 ha; average altitude of 1437 masl) are found within this region. Among the most significant geohydrological aspects of the region is the existence of an important aquifer with deep layers of semi-impermeable calcareous rocks, an intermediate semi-permeable layer, and a highly permeable layer of volcanic lava rock (Jaramillo Monroy et al. 2021). Following the topography of the state, water currents flow and infiltrate from north to south.

Two types of superficial flows are found. The first relates to natural drainage, which is impacted by urban growth and is ephemeral, lacking a clearly defined route because of the high soil permeability. The second system consists of the intricate *apantli* network from pre-Hispanic times, which transfers part of the flow from Chapultepec Spring (1177 lps) (Jaramillo Monroy et al. 2021). After irrigation of crop fields and orchards, 18% of the original volume (approximately, 210 lps) enters the study region through the *apantli* network and finally reaches the receiving vessel of the El Pantano micro-basin (with a flow of 119.8 lps), which represents 10% of the original volume transferred from the Chapultepec Spring.

The apantli irrigation system of Cuernavaca and Jiutepec

The complex network of channels, ditches and aqueducts of the *apantli* form part of the daily water interactions and continue to provide critical cultural ecosystem services for the region. During the Mexican pre-Hispanic period, the management of water and forest areas allowed life to occur and the development of communities, including the flourishing of hydraulic societies in Mesoamerica (Palerm and Wolf 1972; Rabiela and Pérez Espinosa 1985). The function of the *apantli* was to distribute water equally among users, and these constructions had an administrator (Olivares and Sandoval 2008). They determined patterns of human settlement and sites where water ceremonies were performed, permeating all aspects of Mesoamerican life (Olivares and Sandoval 2008). This system has persisted since the time of the conquest, in part because it was co-opted for the cultivation of introduced sugar cane. Currently, and derived from the survey of the *apantli* network we can say that the system continues to be of great importance for various agricultural activities, such as growing sod for lawns, ornamental plants, and some small plots where corn is still grown. It also allows the maintenance of numerous gardens in residential areas and ornamental lakes in luxury subdivisions, as well as constituting biological corridors, recreation areas, and areas used for washing clothes. In many cases, *apantli* also accumulates wastewater and municipal solid waste.

The Metropolitan Zone of Cuernavaca is made up of seven municipalities that are geographically contiguous, and economically and socially integrated. The municipalities with the highest population density are Jiutepec (4161 inhab/km^2), Cuernavaca (1810 inhab/km^2), Emiliano Zapata (1370 inhab/km^2), and Temixco (1282 inhab/km^2) (INEGI 2017). These are included entirely within the Cuernavaca aquifer system, the main source of drinking water for almost half of the state's population. Here, we focused particularly on a smaller region, the El Pantano micro-basin of Jiutepec, which is crossed by the *apantli* system (Figure 1). In recent years, several projects have emerged from the interest of various groups in the Jiutepec community to sustainably utilize the irrigation water contained in the network of *apantli*, canals, and aqueducts from the Chapultepec Spring. Currently, the *apantli* network is under concession of the Civil Association Union of Users of the Las Fuentes Basin, and based on the statutes of this association, federal, state, and municipal laws and programs, a regulation has been developed and proposed. This regulation seeks to establish a fair distribution of clean water for the benefit of associated users and individuals who pay their dues, as well as to protect the *apantli* and their area of influence. It also defines the functions and responsibilities of civil organizations, 'ejidos' (a collective land tenancy system that was institutionalized after the Mexican Revolution), municipal, state, and federal governments, as well as water concessioners, and property owners who live around the *apantli*. This regulation also established the mechanisms for action and coordination of the water protection agencies of the Jiutepec City Council. Jiutepec's municipality has an approximate area of 70.5 km^2 (INEGI 2010), which represents 1.4% of the total area of Morelos. The population density in the municipality is the highest in the state, reaching 2796 inhab/km^2 in 2010 compared to the 364 inhab/km^2 in the state on average in the same year (INEGI 2010). The sustained growth of the population in the municipality of Jiutepec began in 1940, mainly caused by migratory flows from the states of Guerrero, Puebla, and Mexico City, where the poor quality and scarcity of farmland and lack of services and jobs affected a significant part of its population. Growth has intensified since the 1960s because of the industrialization of the region and the availability of employment. Jaramillo Monroy et al. (2021) presented the results of a historical analysis of the evolution of the use and management of soil and water by the various communities that inhabited the study area up to the present. Reviewing historical documents from Mexico's General Archive of the Nation and analyzing documents on the public and citizen management strategies available from 1960 to the present, it was evident that, as well as water has always had a deep spiritual and sociocultural significance in pre-Hispanic towns (Ilyich 1993; León Portilla 1992), the distribution of water under traditional mechanisms was equivalent to some current normative principles (Scarborough 2003).

Morelos is also the state with the highest production of ornamental plants, and Jiutepec and the

Metropolitan Zone of Cuernavaca are the leading municipalities in the state for both open air and greenhouse production (Diario de Morelos 2017). There are also 22 types of aromatic plants that are mainly exported to Japan, the United States, and Canada (rosemary, sage, marjoram, thyme and basil) (Jiutepec City Council, Morelos 2007). The breeding of ornamental fish is also considered an important activity, with Morelos being the first producer nationwide (Jiutepec City Council, Morelos 2007). However, the intensification and diversification of fishing and aquaculture have led to biological hazards such as the introduction of exotic species into ecosystems, causing serious consequences for the conservation of aquatic biodiversity and adverse effects on people who depend on these ecosystems (Kanchi et al. 2021).

As a result of the survey and characterization of the *apantli* network we evidenced that the water from the Chapultepec Spring is distributed through two types of *apantli*-those that run through natural channels made of earth and those maintained with various materials. The latter reach four ejidos by gravity (Chapultepec, Tejalpa, Jiutepec, Acapantzingo and the small property of Jiutepec). The remaining runoff ends up to the east of the spring, and on its way, the water from the *apantli* passes through various urban areas, development, and housing complexes. Finally, it reaches a small conductive vessel called El Pantano, and about 300 meters to the east, there are sinkholes where water infiltrates into the subsoil and aquifer. Given the social, environmental, and economic importance of the correct use of water coming from the Chapultepec Spring and transported through the *apantli* network and aqueducts (concessioned to the Civil Association Union of Users Cuenca de Las Fuentes), we performed the inventory and mapping of the Chapultepec *apantli* system (see data analysis protocol section).

In the 1990s, the *apantli* section of the Las Fuentes irrigation module had a recorded area of 4265 hectares, of which 3472 were ejido lands and 794 were small privately owned properties (Jaramillo Monroy 2021). With more than 2600 irrigation water users, 2260 are *ejidatarios* (communal landowners) and 348 are small properties (Jaramillo Monroy 2021). Results of the survey show that the Las Fuentes irrigation module or section is divided into two zones: one corresponds to the ejidos of the municipalities of Cuernavaca and Jiutepec located in the upper part of the El Pantano micro-basin, and the second corresponds to the ejidos of the municipalities of Emiliano Zapata, Xochitepec, and Tlaltizapán located in the lower part of the micro-basin. The first area is supplied by the Chapultepec Spring, runs through Cuernavaca's municipality and continues toward the ejidos of Jiutepec's municipality.

Along the length of the canals, they vary not only in the materials they are constructed from, but also in their cross-sectional dimensions. In general, stone and earth canals are the largest, followed by cement and stone canals, and stone-filled canals; earth canals are the smallest (Figure 2, Table 1). Finally, 171 sections of channels were characterized, covering an approximate length of 32519 meters between different neighborhoods, streets, and highways in the municipalities of Cuernavaca and Jiutepec (Figure 2). Thus, 12 different types of channels were determined, such as, earth, cement, stone, asbestos pipe, concrete pipe, and several combinations (Figures 2, 3). The most common type of channel (9000 m) was constructed from earth with no coating of construction material. The second most common building materials were those built of cement and stone (8555 m); third, cement (8541 m); and the least common ones were concrete tubes (131 m) (Table 1). The largest flow (615.30 lps) was transported by channels made of cement and stone, followed by those made of cement (280.37 lps), and in third place, those made of earth (74.09 lps) (Figure 4, Table 2). The volumes of water recorded in the Chapultepec springs have tended to decrease since the first records, with a volume of 1821 lps in 1934 (Agrarian Department 1934), 1200 lps in 1981, and 1177 lps in 2015 (Pohle 2015). However, an increase of 3652 lps was observed during the presented study. This may respond to discharges produced by the main urban centers. Regarding the spatial distribution of channels, those with the highest flow were found in the northern part of the study area, where sources or springs are located (Figure 4).

The waters of spring flow through channels that cross the homes and streets of urban areas, some of which have been sealed. Water is used for multiple purposes, including crop irrigation, recreation in the summer, water supply to greenhouses, and domestic use. People living in ejidos consider the water in the area to be the least contaminated; however, the water used by several Jiutepec ejidos is contaminated by household discharges and drainage from subdivisions and surrounding areas of hydraulic infrastructure (Figure 5). Regarding odor, it was not detected in most canals; however, a complete physical-chemical and bacteriological study is recommended to determine the degree of contamination and other physicochemical characteristics of the water.

Regarding the presence of fauna within the canals, we observed fish presence in approximately 27 canal sections. However, in a large number of sections, they were not observed. In this regard, a series of systematic analyses of the *apantles* is recommended to determine the species present, as well as whether these canals can serve as restoration sites for native species such as the Morelos chub (*Notropis boucardi*).

In summary, the hydrological diagnosis, interviews, and fieldwork carried out in recent years in the *apantli*

Table 1. Description of the different types of channels in the *apantli* network, Jiutepec, Morelos, Mexico (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the micro basins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019). Calculation of total length (m), average length (m), and number of sections for each type of channel.

Types of channels			
Type	**Sections**	**Total length (m)**	**Average length (m)**
Earth	64	9001.6	140.6
Cement and Stone	36	8555.6	237.7
Cement	29	8541.1	294.5
Stone and Earth	16	3037.9	189.9
Capped	11	2055.2	186.8
PVC pipe	7	469.2	67.0
Canceled	2	17.2	8.6
Asbestos Pipe	2	38.2	19.1
Cement and Pipe	1	19.2	19.2
Stone	1	109.0	109.0
Underground	1	543.2	543.2
Concrete pipe	1	131.7	131.7
Totals	**171.0**	**32,519.0**	

Table 2. Calculation of the average flow of all sections corresponding to each type of channel of the *apantli* network, Jiutepec, Morelos, Mexico (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the micro basins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019). Considering that 1 m^3/s = 1,000 l/s, the corresponding conversion of the flow data was performed.

Type	Sections	Average flow (lps)
Cement and Stone	36	615.3056
Cement	29	280.3793
Earth	64	74.0938
Stone and Earth	16	211.8125
Capped	11	150.1818
Underground	1	507.0000
Concrete pipe	1	491.0000
PVC pipe	7	57.8571
Stone	1	146.0000
Asbestos Pipe	2	9.0000
Canceled	2	0.0000

network in Jiutepec, Morelos, identified the following problems (Jaramillo Monroy et al. 2021): i.

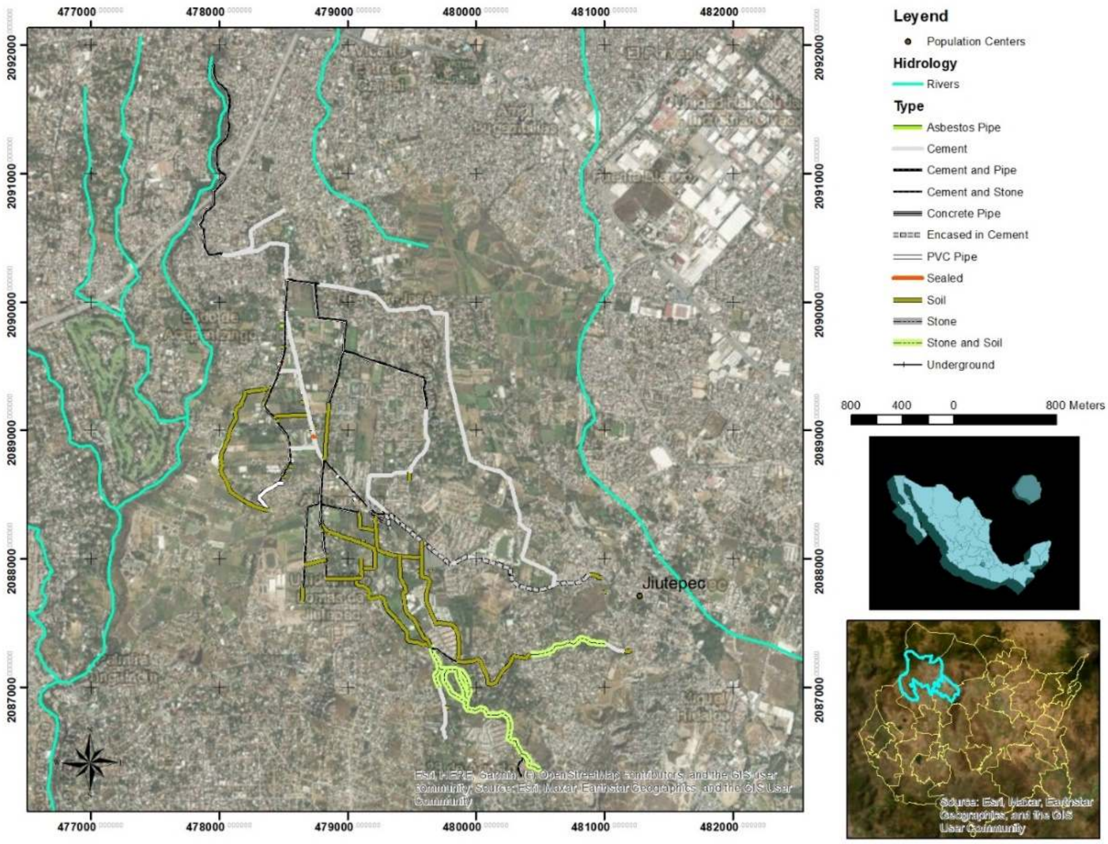

Figure 2. The spatial distribution of the various types of *apantli* registered in Jiutepec, Morelos, Mexico (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the microbasins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019).

The *apantli* or channels are often on private property, which makes it difficult to access them to verify their condition; ii. The channels vary greatly in size due to different interventions in their structure, including very narrow sections of channels that cause bottlenecks and flooding; iii. The water distribution is not the same for all users because some use large quantities and others receive a very reduced flow; iv. There is an accumulation of urban solid waste in the *apantli*, which causes flooding, unsanitary and unsightly conditions, and unpleasant odor (Figure 5); v. Accelerated urbanization has caused the water from the channels to be used by people who are not part of the Union of Cuenca de las Fuentes Users, A.C. without due controls; vi. Some sections of the channels are used as public recreation areas, and some people continue the tradition of washing their clothes in them; vii. Nurseries discharge waste containing fertilizers and agrochemicals into the *apantli*; viii. In the absence of public sewer systems, many houses, businesses, subdivisions and housing units discharge their wastewater into them, and taxi drivers use water from the *apantli* to wash their vehicles, contaminating them with oils and fuel. These problems can be prioritized as follows: impact on tourism and the inhabitants of Jiutepec; sewer system; impact due to hydrometeorological phenomena; land-use change; invasion of the federal zone; population growth; lack of inter-institutional coordination; failure to comply with laws and regulations; financing problems; impact due to water quality; social, political, and cultural problems; lack of institutional action by the Users' Union Cuenca Las Fuentes and the ejido residents (*ejidatarios*) and nurseries.

In conclusion, we recommend the implementation of systematic monitoring of the *apantles'* condition and the water quality they contain over time, in order to enhance the accuracy of estimates regarding changes in the discharge volumes of the Chapultepec Spring and the flow volumes within the reservoir network. It is important to manage the review, consensus, and, where appropriate, official establishment and enforcement of the Management Programs and Regulations for the protection of *apantli* (Jaramillo Monroy and Rodríguez de Gante 2017). The cartography resulting from the study of the *apantli* network can serve as a basis for incorporation into the official cartogra-

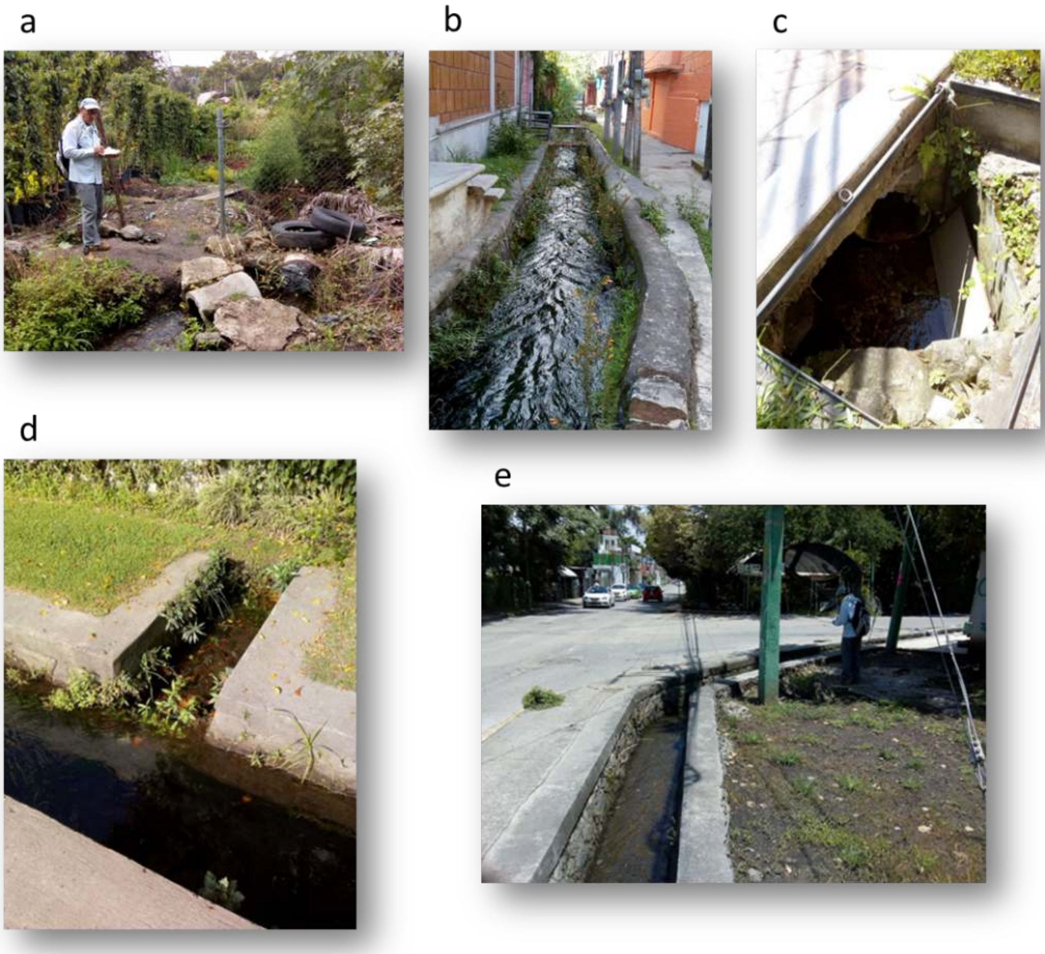

Figure 3. Images of different types of channels registered in the *apantli* network, Jiutepec, Morelos, Mexico. a) Earth channels in nursery areas; b) cement channels; c) PVC and/or concrete pipes; d) Canceled channels; and e) cement and stone channels. (Jaramillo Monroy et al. 2019).

phy and GIS of the municipalities of Cuernavaca and Jiutepec, with the aim of integrating them into the public property registries of the municipalities. This will improve the regulation of land use and construction permits, obligating property owners to protect the water and the *apantli* that cross their properties. It is advisable to form an intersectoral coordination body to observe, monitor, and evaluate the provisions of the Management Program and the regulations for the protection of *apantli* (Jaramillo Monroy and Rodríguez de Gante 2017). To achieve the sanitation and conservation of the *apantli* network and water from the Chapultepec Spring, we propose the following strategic lines of action: i. Capacity building and organizational development so that the population inhabiting the area within the channel network of the Chapultepec Spring has access to information on the sustainable management and conservation of the *apantli*; ii. Conservation and restoration of natural areas and biocultural corridors through the *apantli* system; iii. Management of *apantli* to avoid wastewater discharge and promote the construction, use, and maintenance of eco-techniques for the treatment and reuse of treated water for irrigation of green spaces; iv. Management and handling of household solid waste to prevent it from being dumped into the *apantli*; v. Working toward the declaration of the *apantli* network as a natural and cultural heritage site of Jiutepec and Cuernavaca; vi. Conservation of the historical archeological vestiges found in relation to the *apantli* and dissemination of their characteristics and importance for the region; vii. Management of economic resources for the protection and management of *apantli* and the quality of the water they carry; viii. Planning and sustainable use of the territory and promotion of the establishment and management of protected natural spaces linked to the *apantli* network; ix. Environmental education at all levels, especially for students from schools around the *apantli*; x. Forma-

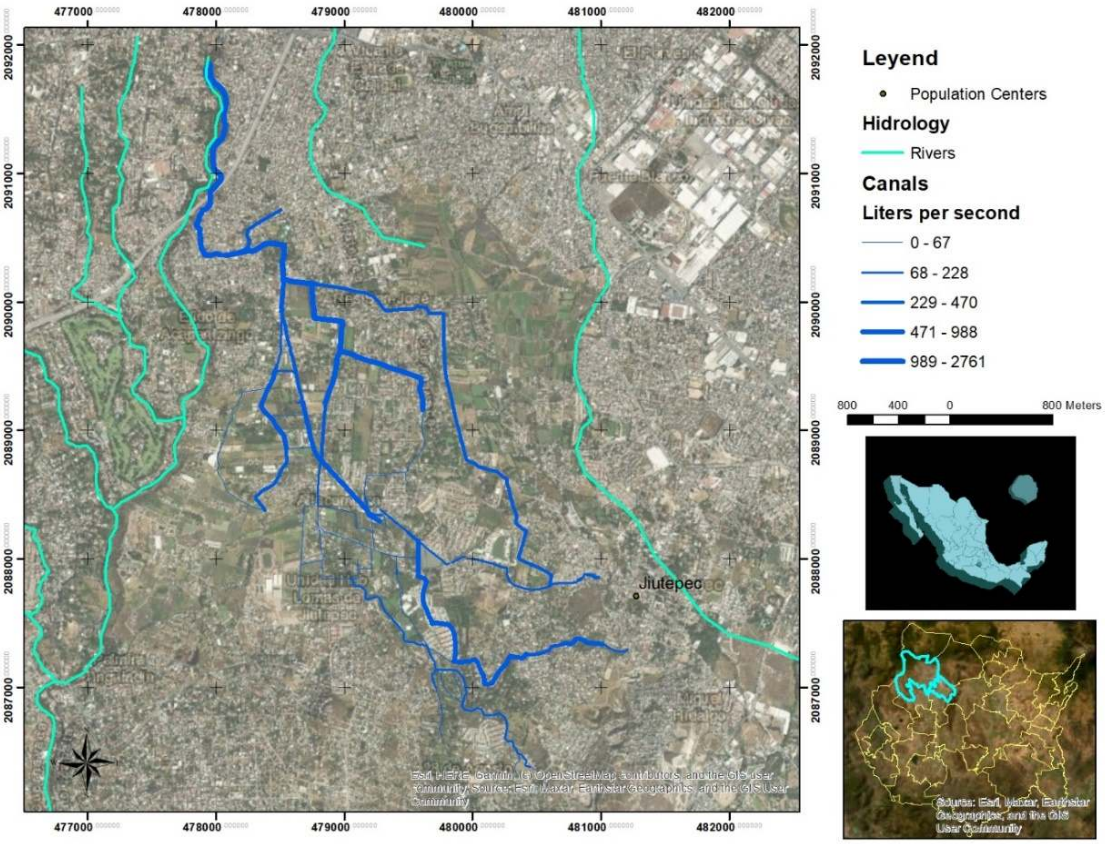

Figure 4. Spatial distribution of flows by section recorded in the Jiutepec *apantli* network, Morelos, Mexico (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the micro basins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019).

tion of an intersectoral Committee for the protection and management of the *apantli* network and official establishment of the Management Program and the Regulations for the protection of the *apantli* system (Jaramillo Monroy and Rodríguez de Gante 2017).

The Pantano Basin Management Program was developed to incorporate traditional knowledge about water use and management into landscape and ecosystem decision-making (Flores-Armillas et al. 2016). This program establishes guidelines to organize the actions and achieve sustainable use of the territory, water, and natural resources in general and the network of *apantli* integrated into the landscape. This program was born as a result of a citizen movement in Jiutepec, which for the last 16 years has been promoting the rescue of green spaces, water, and *apantli* that are still distributed in the municipality. The *apantli* constitute natural and cultural heritage, which is essential for protecting and guaranteeing the sustainable development and quality of life of all living beings that share this territory. It has also been a great achievement to have not only the inventory of the *apantli* network but also the regulations for the protection, use, and distribution of water and the *apantli* system of the Chaputlepec spring located in the municipality of Jiutepec, Morelos, Mexico.

CONCLUSION

Since pre-Hispanic times, water from the *apantli* has flowed through the lands of Mexico's towns, fertilizing the fields and bringing well-being to people. Along their course, they cross cities, ejidos and communities, revive memories, and customs, break down borders, unites people, and organize thousands of men and women daily around its management and defense, renewing season after season, harvest after harvest, a common commitment to life and its dignified reproduction. The historical evolution related to the socio-hydrological and cultural system in the Morelos region was constant, where social interactions have been affected and shaped by the needs imposed by the environment and history itself, the result of moments of glory and well-being, as well as oppression and dispossession. From a broader territorial perspective, the *apantli* networks can be seen as a cultural landscape, a

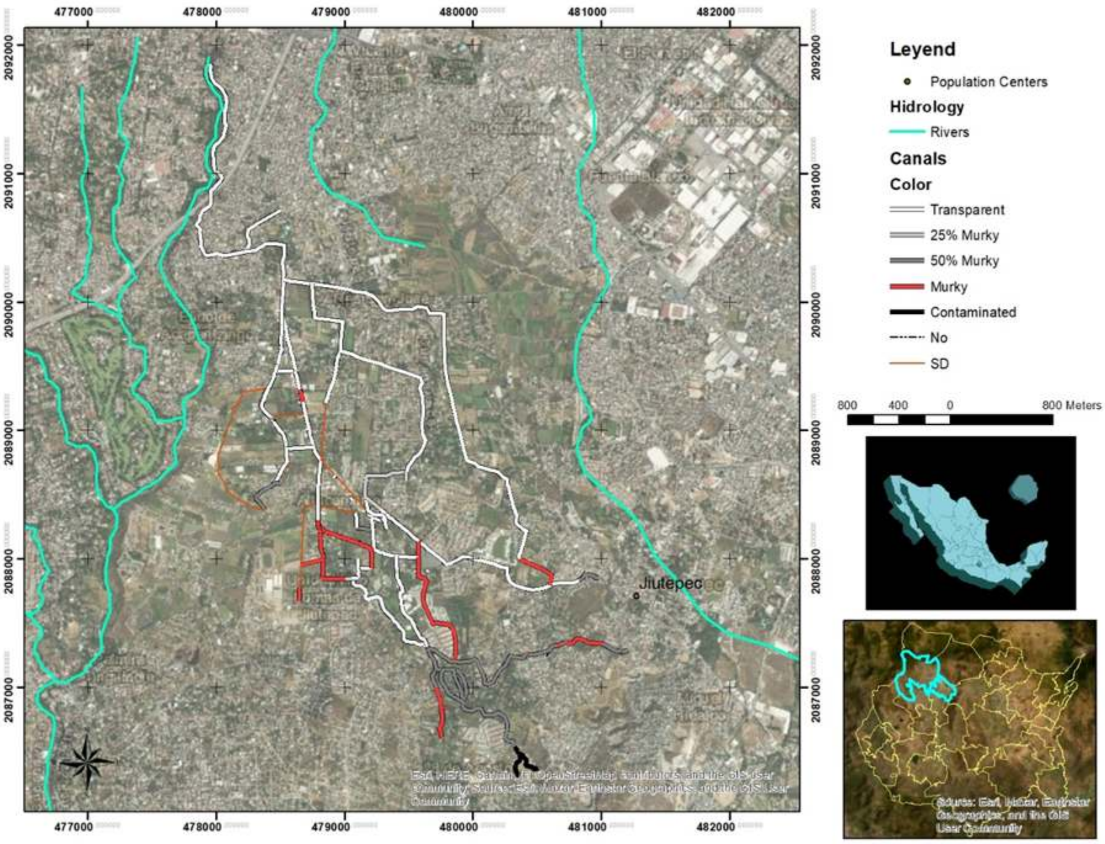

Figure 5. Spatial distribution of physical characteristics of water recorded in the *apantli* network of Jiutepec, Morelos, Mexico (Inventory and cartography of the *apantli* network from the Chapultepec Spring to the micro basins of El Pantano and Joya del Agua and their region of influence, Jiutepec; Jaramillo Monroy et al. 2019).

heritage reality resulting from the interaction between humans and natural factors. As was suggested by Tengberg et al. (2012), this cultural legacy is both tangible and intangible heritage within the landscape that helps to maintain meaning and a sense of collective identity, and its features within the landscape are significant in the present. Thus, *apantli* are not only what the former generations built up but also how it is interpreted, valued and managed by contemporary society in everyday life. Historical artifacts and how practices are connected to historical features within landscapes are considered cultural heritage because we attribute values to them (Muñoz Viñas 2005). Cultural heritage is therefore not static; it is constantly changing, re-evaluated, and interpreted in various ways by different actors.

Cultural landscapes are living and productive spaces where there is a need to balance conservation and development; thus, the conditions to tackle are not completely new to the CES field. In fact, compared to more natural ecosystems, cultural landscapes have much greater potential to supply cultural services. Today, in cultural landscape management procedures aimed at promoting sustainable use strategies, the main challenge is to address the wide range of approaches encompassed by the socioeconomic revaluation of the cultural landscape, particularly the lack of inter-sectorial analysis. Incorporating the Nature's Contributions to People (NCP) point of view into research will provide benefits for planners who need to address the complexities of socio-ecological landscape systems. The advantages of NCP stem from the pressing need to recognize cultural differences in humanity's efforts to conserve and restore nature. The pluralistic approach offered by NCP, along with the adoption of flexible combinations, can foster respectful collaboration between diverse knowledge systems and worldviews, while enabling continuous evolution through practical application.

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DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare no conflicts of interest and have approved its submission to Ethnobiology & Conservation.

CONTRIBUTION STATEMENT

Conceived of the presented idea: EVW and FJM
Experiments were performed: FJM, OP, VHF-A, JL-RdeG
Carried out the data analysis: FJM, OP, VHF-A
Wrote the first draft of the manuscript: EVW
Review and final writing of the manuscript: EVW and FJM
Supervision: EVW and FJM

DISCLOSURE OF AI USE

The authors used Microsoft Copilot AI to assist in improving language clarity in the Significant Statement section only. The content was reviewed and edited by the authors to ensure accuracy and appropriateness.

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