Scan to GIS Methodologies for the Multi-Scalar Representation of Water Landscapes

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This paper outlines a research methodology for the digital representation of amphibious landscapes in the Po Valley. The management of water resources has accompanied the history of settlement systems in northern Italy since the earliest times. Canalisation and hydraulic elements have transformed the appearance of the territory, qualifying the image and identity of different cultures. In the Ticino region, the system of irrigation infrastructure originated with Roman plain drainage and reached a more organic systemisation through the studies of Leonardo da Vinci. This cultural dimension plays a central role in defining the identity of the territory, characterised by a rich natural environment and a substantial hydraulic heritage which, abandoned following industrialisation, now requires recovery and safeguarding. To represent this complexity, the drawer must transform the complexity of relationships into an ordered network of signs. For this reason, the research proposes a step-by-step methodology, progressing from integrated survey to mesh-nurbs modelling, followed by an expeditious census, and culminating in a 3D GIS environment. This multi-scalar model constitutes a unique dynamic organism in which geometries are associated with specific datasets. Through the use of 3D GIS, the research aims to facilitate knowledge of the landscape and support its management by making explicit the relationships between elements and by defining new strategies to raise awareness of the water heritage.

Key Words: amphibious landscapes, water channels, hydraulic heritage, integrated survey, 3D GIS, Po Valley

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INTRODUCTION

The article addresses part of broader research aimed at outlining a methodology for the representation of artificial freshwater pathways.

The motivation for the research lies, first, in the challenge of surveying and restoring an amphibious landscape that is difficult to access or measure and is only partially visible. Second, such a landscape provides the occasion for a cross-cutting interpretation of the territory, enhancing aspects that are particularly relevant today in relation to ecological and environmental sustainability.

The study is oriented towards specific cultural and social interests, as well as the characteristics of water resource management systems in the Po Valley, with particular reference the Ticino region. This region is characterised not only by a complex water system but also by a cultural framework that has linked rural, economic, productive, and social realities over the centuries (Pagani 2017). The construction and promotion of a cultural route that exploits waterways therefore becomes a key for revitalising the territory through culture. As a first step, this process requires the creation of a documentary structure capable of establishing a representative language for this identity system at different levels, from large to small scale. Translating the landscape into conservation and planning practices that are useful for promoting and managing the territory thus requires a specification of the lemmas that compose the complex image of this scenario. Within this necessary process of discretisation, the research primarily responds to a cognitive and conservation-oriented need: to analyse and recover the extensive and locally distributed hydraulic engineering works that modify the characteristics and perception of the territory. This approach facilitates future water resource management actions by fostering awareness of the relationship between humans and the Po Valley landscape (Visconti 2016).

Canals, bridges, small dams, reservoirs, sluices, and conduits exhibit specific characteristics in terms of materials, dimensions, geometries, functions, and states of deterioration. Consequently, within the unavoidable process of landscape transformation, a series of challenges must be addressed to ensure their maintenance and suitability over time. The research therefore contributes to an international and current debate concerning the recovery of the memory of places, the narration of cultural and identity heritage, and the conscious management of water in both urban and agricultural realities. Drawing and digital representation act as a unifying thread throughout this process. They function not only as tools for safeguarding, studying, and disseminating knowledge, but also as expressions of historical reflection and critical engagement with the surrounding environment. The need to control

FIGURE 1 Image of the Confluente, the Last Jump of the Naviglio Pavese
NOTES This is the last basin of the artificial canal, where the water of the Naviglio flows into the Ticino river.

and utilise water heritage throughout history has been key to interpreting the geographical, urban, and environmental transformations and evolution of these places. Of particular importance is the understanding of different modes of representing large-scale systems composed of minimal units (such as engineering works or natural elements characteristic of amphibious environments), which must be revealed in order to support the interpretation, description, and management of these environments defined by the artifice-nature dualism.

PAVIA AND THE CONSTRUCTION OF ITS WATER LANDSCAPE

The plains of Lombardy represent the main agricultural area in Italy in terms of both the quantity and quality of production. Added to the current economic value of the area is the importance of its historical legacy of agricultural techniques and practices, documented since Roman times through the design and construction of canals and irrigation structures (Cremonesi 2001). The waters of the main rivers, diverted and distributed through the construction of an extensive water network, shaped the landscape and enabled the development of agriculture and trade. The numerous Roman ports along Lombard lakes and rivers attest to the transport and exchange of goods and materials originating from the Adriatic Sea. Following long and winding routes, ships sailed up the Po and, from the Mincio, reached Lake Garda, while from the Ticino they landed at Lake Maggiore (Uggeri 1987). With the fall of the Roman Empire, the first major transformations of water systems and landscapes were carried out under Lombard rule (Rao and Salazar 2019). In the early Middle Ages, residential settlements across the plain were sparse, and the landscape was largely characterised by extensive forests and marshlands, which severely limited the development of the agrarian economy (Fumagalli 1985). The imposition of the Benedictine Rule, promoted by Charlemagne, who encouraged the adoption of a single observance across all monasteries of the empire, led from the ninth century onwards, to a significant increase in religious centres throughout the region. Monastic communities settled in residual lands that had never been cultivated. In order to sustain themselves, the monks initiated extensive land-reclamation activities. Well-established techniques of excavation, land levelling, ditch construction, and water conveyance through inlets and locks allowed the drainage of marshy areas and the irrigation of arid lands, laying the groundwork for the great hydraulic achievements of the twelfth century (Bigatti 1995).

Rivers and fountains, the backbone of Lombard hydrography, began to be systematically exploited, fostering early social and economic development. In the 14th century, the Visconti family rose to power over the city of Pavia and its surrounding territories and, with a forward-looking vision for regional development, invested heavily in water-management and hydraulic infrastructure. These interventions enhanced land productivity and enabled waterborne transport, resulting in increased trade and exports. Under Galeazzo II Visconti, in 1359, construction began on the first canal between Milan and Pavia, initially intended for irrigation. The 'Naviglio' was created to meet the irrigation needs of the Visconti Park, which extended behind Pavia castle. A few years later, under the Sforza dynasty, the expansion of the Lombard water network was largely directed towards establishing a navigable connection between Milan and Venice, making Pavia a crucial intermediate stage (Covini 2014). During the second half of the 15th century, rice and mulberry crops became established, and the silk industry was introduced (Fabbricosi et al. 2013) Given the centrality of water to the economy of the area, the 15th and 16th centuries witnessed a significant increase in engineering and hydraulic knowledge.

Substantial changes were therefore made to the water system, including the insertion of locks and basins along canals to allow navigation in both directions, transforming them into genuine transportation and trade routes (Comincini 2012). The richness of hydraulic artefacts and the scale of the Milanese waterway system was a stimulating object of analysis for Leonardo da Vinci. The scientist, who entered the entourage of Ludovico il Moro in 1482, Leonardo resided in Milan for nearly twenty years, producing numerous drawings and writings on fluid dynamics and hydraulic machinery (Lomartire 2019). Studying the navigation locks, da Vinci proposed design modifications to improve their functionality. Moreover, his drawings of devices designed to divert water against its natural gradient suggest his involvement in irrigation projects within the Sforza territories, where significant differences in elevation made water conveyance to higher fields particularly challenging (Di Tullio 2019).

Hydraulic infrastructure development continued under Spanish rule in the 16th century. The Lombard Plain, although distant from the Mediterranean and Adriatic ports, could be connected to them through the strategic management of water resources. This required the construction of navigable waterways capable of regulating the great rivers that marked the landscape, namely the Po, Ticino, and Adda. Beginning with the construction of the Naviglio Grande (12th century) more than seven hundred years of projects, excavations, and flow diversions transformed the plain between the Ticino and Adda rivers into a dense and complex navigation network, known today as the 'Milanese Navigli System' (Boatti and Prusicki 2018). The major canal to be completed was the Naviglio Pavese, finalised in the 19th century, which directly connected Milan to the Ticino River and channelled the majority of river traffic to and from Venice. The new hydraulic network defined by Navigli increased water transportation, ensured continuity in river navigation, and boosted agricultural production. Its multifunctional character formed the basis for the development and economic growth of the plain (Bigatti 2020) Water, managed in its volume and flow, thus became a primary source of energy production.

By exploiting the drops created by navigation locks, the first hydroelectric power stations were established, while the consistent distribution of water to artificial canals enabled the continuous operation of waterwheels and mills (Chierico 2019). The role of the Navigli in the construction of Lombardy's landscape is significant at both the eco-

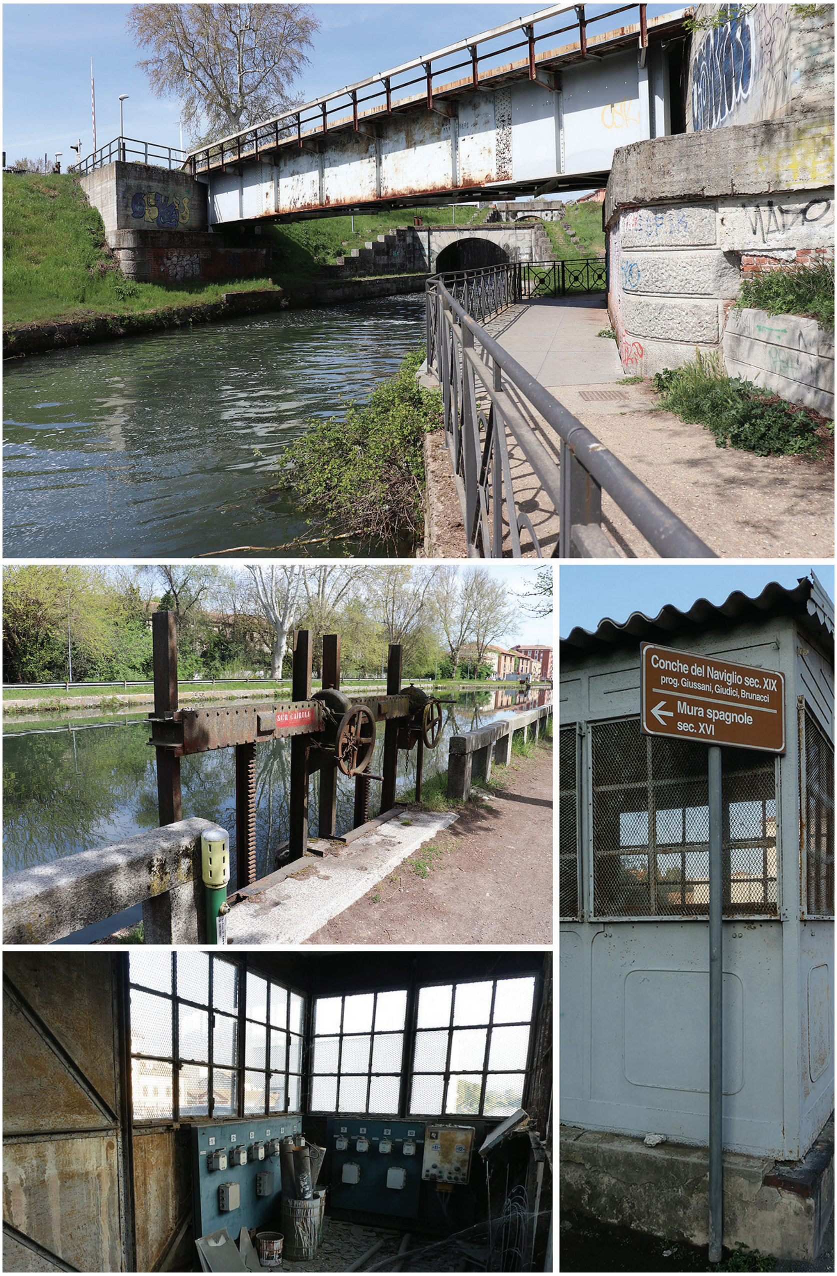

FIGURE 2 Views of the *Naviglio Pavese* and its hydraulic works

NOTES From above, the *Biconca Botanica* and the railway bridge crossing it; the system of embankments near *Borgo Calvenzano;* and exterior and interior of a control cabin.

nomic and social levels, with far-reaching repercussions. The entire system underpins processes of interconnection between diverse urban and rural realities, supporting the formation of a polycentric settlement network across the territory, which in turn permanently shapes the landscape.

The arrival of the railway in 1862 led to a gradual decline in traffic along the Pavese Canal. By the late 1930s, the canal had lost its function as a transport route and was gradually abandoned, as were the commercial facilities and services dependent upon it.

The legitimization of the infrastructure's value dates back only to the end of the 20th century, within an overall rediscovery of Lombardy's heritage of industrial archaeology. In this context, the canal came to be recognised as having unique characteristics within the wider Navigli system. Its slow and troubled construction allowed engineers to incorporate, already at the design stage, improvements developed in other canals and to benefit from the increased hydraulic expertise available at the time of construction.

Today, this cultural dimension connected to the water landscape plays a central role in determining the identity of the area and is characterised not only by a rich natural environment but also through numerous works. Farmsteads, churches, villages, and significant architectural complexes animate a landscape structured around water routes, a landscape that now requires systematic study in order to recover and preserve its historical memory.

OBJECTIVES AND METHODOLOGY

The research concerns extensive landscapes characterised by significant point elements that cannot be simplified. Its aim is to define the most appropriate documentation and representation strategies using digital technologies. Therefore, to define a digital database for the management of the amphibious landscape of the Pavia Plain integrates several logical, cultural and applicative sequences, articulated across multiple scales.

The Construction through Archetypes

In the rural landscape of the Pavia hinterland, farmhouses, networks of primary and secondary canals, and cultivated fields constitute the characteristic elements that define the universally recognisable image of the area. Canals and road networks, which cut through the continu-

FIGURE 3 Semantic Representation of the Amphibious Landscape into Surfaces, Lines, and Points

NOTES From above: cultivated fields, synthesized through drawings into the four main types (rice fields, poplar groves, *marcita,* and wheat fields); navigable canals and smaller seasonal irrigation channels, accompanied by a diagram illustrating the operation of the locks; and two examples of minor hydraulic elements – a sluice gate and a bollard – alongside a diagram of a farmhouse, representing the specific identity-defining features of the territory.

ous surface of the fields, affect the perception and organisation of physical space. The resulting mesh of paths is readily legible and functions as a defining sign that translates the place into an image.

The structuring of a representational system composed of surfaces, lines, and points (Lynch 2006; Bianchi 2019) forms the basis of an archetypal model of the landscape's distinctive features. This synthesis enables the development of graphic operations that transform 'signs' into 'forms,' making explicit the complexity of relationships among the constituent elements while preserving the signifier of the structure to which it belongs, namely the place itself (Parrinello and Picchio 2017; Galasso et al. 2021).

Crops are represented as surfaces, irrigation networks as lines, and minor hydraulic works as points. By moving to a smaller scale, to enable a better understanding of the relationships among the various elements within individual areas, a set of 'archetypes' has been defined

(Venturi et al. 2010). These simplified three-dimensional forms briefly explicate the morphological characters of the elements, making them easily recognizable within the general representation of the area. These simplified three-dimensional forms briefly explain the morphological characteristics of the elements, making them easily recognisable within the general representation of the area. In this process, surfaces acquire thickness, lines become cylinders, and points take the form of cubes or spheres. The use of symbolic language defines a valid coding system for each element into which the landscape has been decomposed. The alphabet of forms that constitutes this language is composed of simple solids, aggregated according to specific relationships that emerge from visual analysis (Oldani 2020; Parrinello and Porcheddu 2023). Within this framework, surfaces (crops) are connected to, yet distinguished from, one another by lines (canals and irrigation channels), while points (hydraulic artefacts, bridges, and related structures) are located on both lines and surfaces, defining and articulating their interrelationships.

The Multiscalar Census

To define a representative system of this landscape, useful both for its knowledge and enhancement and for its management by consortia and associations in the area, it is necessary to undertake a more in-depth analysis, which would allow for the identification of site-specific characteristics. Therefore, an initial reconnaissance of the plain was conducted, taking into account not only the major waterways and urbanised portions but also agricultural and rural areas.

In addition to assets traditionally considered part of the hydraulic heritage, several recurring 'elements' typical of the irrigated landscape of the plain were identified: the crosswalks of canals or ditches, usually stone or brick structures of modest size; the punctual trees rising at the margins of cultivated fields, often signalling the location of a crossing that would otherwise be difficult to detect in the horizontal expanse of the landscape; yellow or green posts topped with red cones or flaps, to signal the underground passage of methane pipelines; wooden or metal sluice gates for water diversion; brick farmhouses flanked by metal or concrete silos; and the low architecture of historic villages. These elements contribute to the meaning of the landscape and, for this reason, they should be taken into account in the processes of discretisation and geometric decomposition, as well as in digital documentation, invento-

FIGURE 4 Landscape Census Methodology

NOTES From the left: example of infographics cards structured for landscape analysis; field compilation; and a conceptual diagram showing how queries operate in the final model.

rying, and graphic translation phase. To support this process, specific census forms were developed, designed to be completed directly in the field, through the use of a mobile phone or tablet via freely available applications. The cards summarise the analyses that the operator performs on the irrigated landscape, with the aim of establishing a repeatable and updatable system of categorisation and classification that can subsequently be transferred to a GIS (Geographical Information System) platform.

To ensure the most comprehensive landscape analysis possible at the scale of crops, canals, and hydraulic elements, three different types of census forms were created, corresponding to surfaces, lines, and points. This structure allows adequate space for the description of each component while ensuring that all elements are queryable within the GIS platform. Each tab was designed to achieve a different level of detail, referring to that of the model to which it relates. The three types of cards follow a common logic, they differ in their specific data fields. In general, the first section, 'general framework,' provides the identification code of the surface, line, or point under investigation, along with planimetric images necessary to understand its position about its surroundings and its main morphological characterizations. Specific fields are provided for each fillable item, as well as the possibility of taking photographs directly in situ or to add notes if necessary. The second section, 'analysis of surfaces/lines/points,' focuses on the decomposition of the landscape into its main components and their geometrisation. Geometrical simplification is articulated through a set of requests – ranging from photographs to operational diagrams and technical specifications, that guide the operator, enabling each element to be classified and rendered inelligible in its complexity to users.

Integrated Fast Survey Strategies

The current urgent need to geographically model our environment and to visualise it in three dimensions, using satellite imagery and digital products derived from high-resolution laser scanning, has already had, and will continue to have, a significant impact on protocols for the management and enhancement of heritage, natural and built (Dell'Amico 2021). Technological advances and the recent market availability of expeditious acquisition devices, and related data-processing and post-production software, have also opened up new possibilities for the acquisition of heterogeneous landscape data (Pancani and Bigongiari 2019). Nevertheless, being able to digitally transpose the complexity and multiscalarity of a natural, albeit human-shaped, environment presents several challenges, which are further amplified when the water element is present. Indeed, developing a pathway to knowledge of an amphibious landscape requires the comparison and representation not only of what is visible but also of what remains hidden, the graphic restitution of minimal morphometric variations, and the depiction of highly changeable *stabilitas loci* (Parrinello and La Placa 2021).

In a landscape characterised by extensive cultivation, horizontal development prevails over vertical references, while fields, embankments, and beds change seasonally in response to agricultural cycles they undergo. It is necessary to take into account the flow characteristics, perennial or seasonal, of the watercourses that traverse the area, as well as the consequent transformations of associated vegetation. For this reason, and in line with the decomposition of the landscape and the definition of archetypes different acquisition methodologies were adopted. These methods aim to describe the complexity of the system at a spatial scale while simultaneously narrating, at an architectural scale and with a high level of accuracy, the specific characteristics of the hydraulic heritage elements present there (locks, elevated canals, norias, etc.).

The three-dimensional, multi-scale database obtained from the survey must contain, for each identified category (surfaces, lines, and

FIGURE 5 Images of the Integrated Documentation Campaign

NOTES Top left: acquisition of control points with Asta GPS; on the right: documentation of the banks and beds of the irrigation canals with Mobile Laser Scanner; on the left, in the centre, structuring of the flight plan for photogrammetric acquisition at altitude; and at the bottom left documentation of the elements of the hydraulic heritage using a Terrestrial Laser Scanner.

points), useful information to simplify the agricultural and productive management of the investigated system. With regard to surfaces, corresponding to the characteristic crops of the Pavia plain (such as paddy fields, poplar groves, *marcita,* and cereal crops), the digital duplicate should provide information on the types of sown crops, elevation and slope orientation, and boundary conditions, whether defined by watercourses, earthen embankments, service roads, or rows of trees. For lines, namely irrigated and/or navigable canals, classified as major, intermediate, or minor, the digital duplicate will have to contain information regarding the slope, direction of flow, geometry of the banks, morphology, and dimension of the beds. Such data allow the calculation of specific parameters, for example, for quantifying the flow of water intended for irrigation. The operator must also be able to use the dataset to carry out descriptive investigations into the location, state of preservation, and types of materials used for point components, ranging from navigation locks to mechanical and hydraulic works.

The activities involved documenting and analysing *il Cassinino,* a small settlement located north of Pavia on the right bank of the *Naviglio Pavese.* The area includes different types of cultivation and various classes of canalisation, as well as numerous valuable historical hydraulic features. The entire system defines a *unicum* of settlement and landscape covering an area of approximately 12 hectares. To proceed with its acquisition and digital transposition, the map was divided into circumscribed areas. For each selected area, an acquisition path was preliminarily programmed with mobile laser scanner instrumentation, ideally decomposing the space into closed, overlapping circuits of approximately 500 m each, to reduce the drift error of the instrument. Before each acquisition, some large (50 cm × 50 cm) photogrammetric targets, visible from UAV imagery, were strategically placed. On these targets, points were materialised and surveyed with both the mobile laser and an E-Survey GPS rod. This procedure made it possible to use known WGS coordinates during processing and to georeference datasets acquired through different instruments – such as MLS and UAV point clouds – within a common spatial reference system.

Approximately 12 hours were required to complete the MLS acquisition over the entire area. The greatest difficulties were encountered in undeveloped zones, owing to water refraction and the absence of vertical reference elements within the operating range of the instrument. The presence of water was partly mitigated by conducting seasonal surveys. By taking advantage of the winter months, it was possible to capture the rice crops (which are covered with water in spring and summer), as well as certain minor canals that are periodically dry. However, water has constant flow in the intermediate and major canals. Therefore, to minimise errors during data acquisition, the circuits were reduced to half the size originally planned.

The UAV-based acquisition campaign likewise involved subdividing the entire survey area in the plan. The rationale for partitioning was based on instrument performance (Barba et al. 2019; La Placa and Picchio 2022) and minimum flight height, allowing for a planned Ground Sample Distance (GSD) of 1 cm/pixel, a calculated resolution considered sufficient to obtain a detailed point cloud. In particular, due to the presence of trees, overhead cables, and other possible interferences, the flights were planned at an altitude between 35 and 40 m above ground level. Documentation activities of the minor hydraulic heritage, on the other hand, focused almost exclusively on the Cassinino basin (water jump on the *Naviglio Pavese* dating back to the 1800s and all the widespread features along the canals). In addition to MLS acquisitions, targeted documentation campaigns were carried out for each hydraulic element in order to produce an informative digital duplicate capable of supporting the evaluation of future maintenance strategies and potential reuse scenarios for the basins. Concerning the increased level of detail required, a documentation process was defined using ground-based SfM photogrammetric techniques and scans acquired with fixed-position laser scanners (Leica Geosystem RTC 360 instrument).

From Survey to Model: Defining Levels of Detail

To also make the database verification and model-building phases as 'expeditious as possible,' a series of comparative tests were conducted using different software platforms to identify the most effective procedures for the three-dimensional reconstruction of surfaces, lines, and points (i.e. landscape archetypes).

For surface modelling, namely the construction of the Digital Terrain Model, DTM, (La Placa and Doria 2022), experiments were conducted to develop semi-automatic processes for extrapolating terrain information while still ensuring a final output that was readable and metrically reliable, and comparable to a manually generated model. To accelerate the entire process, Leica Geosystems' 3DReshaper Point Cloud Processing Software was used. Using 3DR, it is possible to generate a DTM directly from the point cloud without the need for prior removal or filtering of trees and vertical elements (Aschoff 2004; Wallace 2014; Zhong 2017). The operator intervenes only by adjusting a limited number of parameters, manually set to guide the software towards the most appropriate processing strategy for the specific survey area. The rapid execution of the automated processes enabled numerous extraction tests, facilitating the comparison of DTMS obtainable from different databases and leading to the selection of the MLS and UAV integrated database as the most suitable. The terrain obtained collects data not only on the cultivations, and the objective of the study, but also on embankments, canals, and roads. The digital product thus configured is easily manageable and contains the intended geometric and morphological information; however, this information has not yet been made explicit, subdivided, or systematically organized. Therefore, to be able to obtain individual models specific to each surveyed crop and digitally restituted, the DTM was decomposed into discrete portions. Using 3DR software, the overall model was then duplicated and assigned to separate layers, allowing each copy to be managed independently. At the conclusion of the decomposition and duplication process, a distinct model was produced for each crop type, georeferenced in relation to the others and catalogued according to its inclusion within a specific macro-surface. The result is a digital product that provides indications of elevation, slope direction, and boundaries of the perimeter of the different plots. However, if the level of geometric detail has been achieved for the analysis ofwaterscape surfaces, the informational component (in terms of crop type, and the presence of irrigation heritage elements) still needs to be made explicit. Likewise, it is necessary to establish connections between the different surfaces and the lines and points that constitute the landscape system.

For the restitution of the canalisation, several exploratory tests were conducted using parametric software. The results proved satisfactory only for major artificial canals (e.g. the Naviglio Pavese), characterised by well-defined banks and beds. For intermediate and minor canals, which are marked by highly irregular riverbeds and banks, a different methodology is required

to ensure maximum fidelity between the digital duplicate and the acquisition database. For this reason, selected points corresponding to embankments, banks, and riverbeds were extracted from the MLS point cloud using the 'multipick' command in Cyclone software. These data were then exported and imported into Rhinoceros, where, using the 'patch' command, a through surface was generated. Although necessarily approximate, owing to the limited number of selected points, this approach enabled the reconstruction of the morphology and alignment of both banks and bed. Model development from the 'patch' command shares the same logic as DTM generation with semi-automatic processes, although it produces a different result in terms of surface features. Therefore, some tests of terrain extraction related only to canalizations were carried out on 3DReshaper software. To ensure the highest possible vertical accuracy, the MLS-derived point cloud was selected as the primary dataset. The surfaces generated through this workflow consist of polygonal mesh models composed of vertices, edges, and faces, that use a polygonal representation to define the three-dimensional geometry and can be readily integrated with surface-based models. Mesh models make it possible to generate ele-

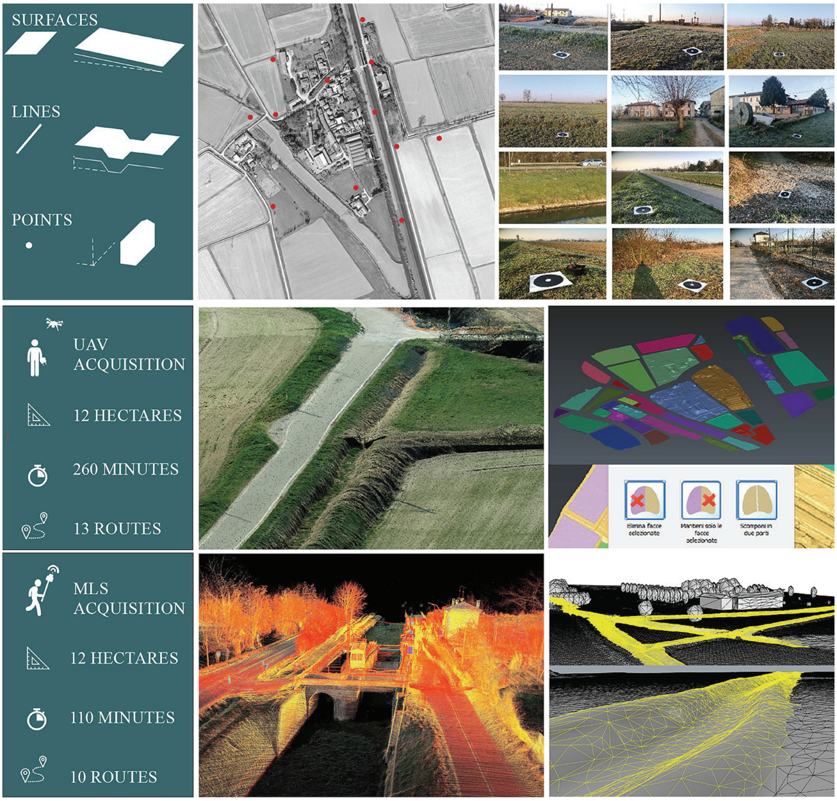

FIGURE 6 Methodological Summary from Analysis to Detection to Multiscalar Modelling

Continued on the next page

mentary shapes, but also to apply modifications to them, increasing, for example, their smoothness levels, a feature that makes them suitable for achieving the set LoDs. Nevertheless, while the morphological and geometrical aspects of the canalisation systems are adequately resolved, several parameters essential for water management – such as flow rate and seasonal or continuous use – remain implicit and must be explicitly associated with the corresponding digital duplicates.

From the datasets obtained with punctual acquisitions of the elements of the hydraulic heritage, specific geometric analyses were carried out using two- and three-dimensional drawings, aimed at understanding the functioning of each artefact. It is therefore necessary to define a catalogue of elements from which standardised prototypes can be developed for each type: locks, bollards, Vincian gates, etc. Each pro-

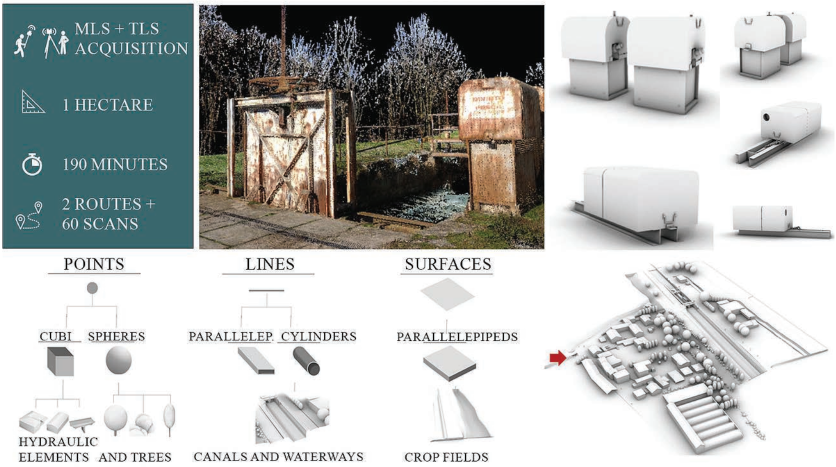

FIGURE 6 *Continued from the previous page*

NOTES Top: disposition of targets to ensure integration of survey datasets; centre, acquisition process, point cloud, and model for surfaces, lines and points; bottom: summary of the construction of the different models and their integration into a single three-dimensional system.

totype must achieve a level of detail sufficient to capture its specific morphological and functional characteristics, while maintaining a metric tolerance of less than one centimeter in the representation. These models must subsequently be integrated within the digital products produced for the representation of canals and cultivated areas. Their interaction forms the basis for establishing a coherent dialogue between points, lines, and surfaces. In this context, the standardisation of elements and their digital cataloguing allows them to be applied to the representation of additional portions of the territory, ensuring the replicability of the process and significantly reducing the time required for future surveys and modelling.

To ensure the achievement of the LoDs established for the hydraulic heritage elements, several modelling experiments were conducted, employing both semi-automatic and manual processes. For each typology, the most representative element was selected, with particular attention to the precarious condition of nineteenth-century iron components. To be able to deepen the understanding of the various constituent parts of the analysed artefacts, a process of detailed modelling was initiated, beginning with two-dimensional drawings created in AutoCAD and supported by photographic images and photogrammetric models. The high level of detail prescribed serves two purposes: first, to understand the functioning of the different mechanisms, which is essential for the facilitation of the management of the irrigation system; and second, to recover the historical morphologies, thereby preserving over time the identity memory of this heritage that is slowly disappearing. Following a series of evaluations, the methodology included the use of Rhinoceros software, for the possibility of generating NURBS geometries. These precisely define any shape, making it an ideal tool for assisted modelling (Parrinello et al. 2020).

Sections and plans of the various objects were then exported from AutoCAD and inserted into Rhinoceros. Once the unit of measurement was set, the components of each artefact were modelled by extrusion of polylines and by the creation and association of solids. Given that modelling timelines can be extensive and vary depending on the type of artefact to be reproduced, it is important to note that each element of the hydraulic heritage of the plain only needs to be modelled once. Depending on the standardisation of the types and their systemisation within the abacus, each model then only needs to be duplicated as many times as it occurs in the investigated area and placed on the corresponding surface or canal. Once the digital duplicates of the surfaces, lines, and points deemed significant for the landscape under investigation were created, each at the predetermined level of detail, they were integrated into the system to build a multi-scaled model. However, even when combined, these elements alone were insufficient to fully convey the spatial narrative, which is constituted by additional elements and the relationships among them, that accompany and give meaning to the chosen surfaces, lines, and points. Components whose absence would immediately alter the perception of a given space were therefore modelled: vegetation, buildings, and street furniture. To avoid overloading the final model, these elements were placed on a single level and represented in communicative but simplified iconic forms (Passamani 2016).

From the Level of Detail to the Level of Knowledge

Representing an amphibious landscape requires dealing with a multiplicity of changing elements that are often difficult to assimilate into simple geometric conformations. This challenge is compounded by the need to reconstruct the equally complex relationships among these elements (Purini 2007).

In this sense, the construction of the multi-scalar model aims to achieve several objectives: a documentary objective, for the recovery of the identity elements of the landscape system; a communicative objective, for the dissemination of knowledge and the enhancement of the visibility of hydraulic works; and finally, a management objective, implemented through the production of reliable tools for understanding the morphology and spatial distribution of water-related heritage. In particular, the results related to the latter objective are conceived as digital models to support public administrations, as well as entities and associations involved in the maintenance and proper functioning of irrigation infrastructures. The degrees of spatial reading achieved, quantitative for the representation of waterways and crops, and qualitative for elements of the hydraulic heritage, encourage the construction of a digital structure organised by levels.

Surfaces, lines, and points, managed separately and each according to its specific LoD, must then be assembled and associated with specific data to form a single organism, which will allow an advancement of knowledge, in terms of quality and quantity of information over the currently available three-dimensional visualisation modes (Galeazzo 2024). Each digital component created must remain legible in relation to its context and be enriched with cognitive data not directly conveyed through visual representation. Therefore, a methodology divided into phases has been studied: the first phase involves unifying all modeled components within a single database; the second consists of inserting each model into the GIS platform; and the third entails the digital integration of the model through the inclusion of the census cards.

For the development of the first phase, Rhinoceros was chosen for the assembly of surfaces, lines, and points. The software offers two advantageous possibilities for the work process since it allows both to handle NURBS models (point elements) and meshes (surfaces and lines), and to switch between high-poly and low-poly models, reducing the mesh number automatically. In addition, the operator can export surfaces and lines from point-cloud model generation software and import them into Rhinoceros in as many layers, so that each component – such as individual canals or crop fields – can be selected independently. The duplicate is thus an expression of complexity and is capable of describing both quantitative-territorial and qualitative-landscape aspects. However, the optimised multi-scale model thus obtained still requires enrichment with additional data and association with prepared census cards. This action involves integrating the three-dimensional duplicate into a GIS platform, where the weight of the imported object can significantly affect movement and visualisation (Biljecki et al. 2014; Picchio and Dell'Amico 2017).

[472] To achieve a three-dimensional geographic information system that meets its intended goals, it is necessary to establish within the platform a two-way correspondence between the level of detail and level of knowledge (LoK – Level of Knowledge), even in multi-scalar models. Each prototype (or type of shape identified) must correspond to specific information within the general model, and each three-dimensional component must be linked to a dataset that can be consulted on specific entries on a census card. All three census cards (see 3.2) include a nomenclature code in the upper right-hand corner. This is the most significant information, as the name serves as the unique code that links the card to its corresponding three-dimensional reference element, which is also identified using the same code. Card type 1 guides the user in the analysis of each field (surface), card type 2 in the analysis of water canals (lines), and card type 3 in the analysis of hydraulic elements. Card 2 has the same configuration as card 1, but in accordance with the increased level of detail required for canal models, it also enables more in-depth analysis. Card 3 similarly follows the structural logic of the previous cards, but, in line with the LoD required for hydraulic heritage models, it allows for the development of highly detailed analyses. In particular, card 3 includes dedicated sections on the state of preservation (very poor, good, excellent), the period of construction (current or historical), and the material of which the element is composed (metal, brick, stone, wood, or mixed).

These cards thus contain information that the separate, or even combined, digital models cannot explicitly convey. On the GIS platform, the multi-scalar landscape model is already present. As a result of the census, it is capable of collecting a particularly large amount of data, especially given the extent of the case study and the potential for replicating the method across the Pavia irrigated plain. The key aspect, however, is not only the quantitative richness of the data that can be collected, but also that, once integrated with the digital model, the data render it informative and therefore queryable, allowing the development of thematic analyses and specific syntheses (Xu et al. 2021; Picchio et al. 2022).

Data linkage between the census and the model is achieved by im-

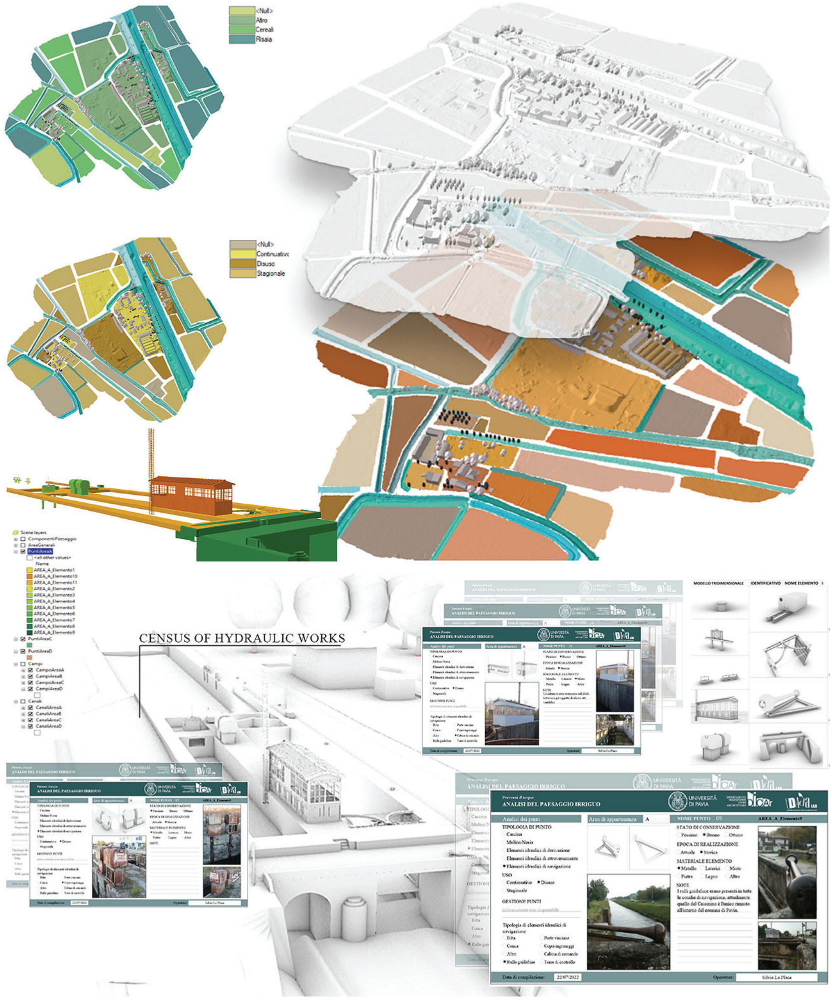

FIGURE 7 The 3D GIS Platform

NOTES Top: thematic maps illustrating the type of cultivation, the time of use (seasonal or continuous) of the fields, and the flow rate of the water channels; bottom: detailed queries on the minor hydraulic heritage, with the associated census cards open.

porting both into the GIS platform, where the multi-scalar model forms the basis of the new system, which must be user-friendly and continuously updatable. At this point, once these two data sources have been linked, the conditions are established for the extraction of information. In this regard, GIS platforms allow for two types of use:

a direct one, through the query of the individual entity; and a graphical one, through the generation of thematic maps elaborated based on parameters (card fields) and values (card compilation values) (Malczewski 2004). The first method generates a list of textual information, providing a comprehensive and detailed description of the queried entity. The second method generates a graphical output, which is more immediate and intuitive, allowing the simultaneous communication of a substantial amount of information. Maps generated in this way thus function as a synthesis of information related to a specific field of the census database, expressed simultaneously across all components of the system. Using the graphical products from this method, it is possible to gain an overall understanding of the irrigated landscape, while selectively highlighting chosen parameters. Among the possible thematic maps that can be produced are: spatial type maps (indicating types of crops, modes of crop use, presence of flora or fauna, and the location of historical hydraulic elements); maps illustrating irrigation status (types of canals, permanent or seasonal water availability for irrigation; presence of hydraulic diversion elements; types of obstructions in canals; and locations of crossing structures); and maps depicting hydraulic heritage elements and their state of preservation (types of artefacts, groupings related to management, and types of observed degradation).

The model computerisation process was run on two different GIS platforms: the open source QGIS and the proprietary ESRI ArcGIS, to establish advantages and disadvantages of each. The GIS 3D system, in both platforms, integrates the reality-based model with the census information (composed of fields and census card values) correlated through key fields. The information model managed via the open-source software QGIS allows the end user to operate the system locally and without an online connection. The system can be continuously updated over time, even in cases where specific functions need to be implemented independently. However, the model's potential is limited, as real-time cloud sharing requires the installation of a plug-in, and the platform struggles with the management of large volumes of three-dimensional data. In contrast, ESRI ArcGIS system provides the infrastructure to produce maps and associated information and to make them openly accessible via the Web, enabling cloud-based sharing with multiple users and real-time updates. This functionality, however advantageous, requires a stable wi-fi connection for viewing and operation, and is subject to potential system variations. The model is dependent on the proprietary software's lifecycle and updates, as it is not open source. Nevertheless, the Georeferenced Information System allows the production of minimum expected outputs (such as thematic maps and point-specific information) using either software. Consequently, the system can be proposed to administrations and consortia using the platform that aligns with available budgets and the technical readiness of staff. In any case, both the model and related information can always be exported and imported from one platform to another in the form of shapefiles.

CONCLUSIONS

Undertaking a study on the representation of water landscapes today is both appealing and challenging. However, given the growing value of water as a universal heritage to be protected, research and projects in this field are increasingly numerous, supported by new European legislation and regulations. The attention that human societies have historically devoted to water – and continue to devote – has engaged scholars across a wide range of disciplines, driven by the shared need to identify the most effective methods for managing and controlling this essential resource. Cities have evolved over the centuries, especially regarding productive sectors, by looking at natural waterways and, in many cases, modifying their morphology following the construction of artificial ones. Transportation, communication networks, expansion, and territorial boundaries have all depended on these cutting and connecting elements. For this reason, irrigation infrastructure is an indispensable key to understanding both urban and territorial spaces. Studying waterways allows us to explain the location of rural settlements, valuable architecture, monastic complexes, factories, and industries, as well as current road networks, many of which follow the course of former waterways. Analysing the evolution of water networks provides a basis for understanding the spatial principles that shaped contemporary forms and geometries and supports the informed planning of future urban developments. The disciplines of drawing and surveying, which underpin this research, make it possible to capture not only the morphology of the territory affected by the waterways but also the technical and landscape characteristics of the watercourses themselves, along with the types of hydraulic artefacts present, which, by their very presence, help to define and qualify these landscapes.

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