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GIS INTEGRATION OF HETEROGENEOUS DATA FOR THE ARCHAEOLOGICAL TOPOGRAPHY OF THE 'ACQUEDOTTO DEL PARADISO', SYRACUSE

1. Introduction

The aim of this paper is to update our knowledge of the archaeological topography of Syracuse by reassessing the available legacy data regarding its waterscape, using both traditional methods and new digital technologies. Among the infrastructures dedicated to the water supply of the Corinthian *polis*, the 'Acquedotto del Paradiso' was one of the most important, extending approximately 2500 m along a NE-SW axis from *Epipolai* towards Ortigia through the *Neapolis* and *Achradina*. The earliest reference to the Syracusan aqueducts is in Thucydides' *Peloponnesian War*, where the historian mentions the cutting of the underground conduits that supplied drinking water to the city during the siege of Syracuse in 414 BCE (Th., VI, 100, 1). These aqueducts, therefore, were already functional in the 5th BCE. Their memory was never lost throughout the millennia, as evidenced by modern antiquarian's writings (Fazello 1558, 93; Capodieci 1813, 278-279). However, first systematic surveys were only conducted in the 19th century thanks to J. Schubring (1865) and to F.S Cavallari and A. Holm, who produced a map that became the cornerstone the research on ancient topography of Syracuse (Cavallari, Holm 1883, tab. 1, I-VIII). The archaeological data on the aqueduct were few: so, scholars have continued until recently to use these data without integrating them with new surveys, new analysis of construction techniques and, where available, repositioning them in their exact locations thanks to the new topographic tools.

This work illustrates how old reports, historical maps, and data from autoptic field surveys carried out with innovative technologies and traditional methods can work together in a Geographic Information System (GIS) environment (Fig. 1) (Tortorici 2016; Brancato 2020). This integrated approach can shed new light on the route and chronology of the Acquedotto del Paradiso, infrastructure always known throughout the centuries although never adequately analysed.

2. The applied method

2.1 *The topographical base*

The initial step involved establishing the topographical base within the GIS environment using the open-source software QGIS 3.28.15. The WGS

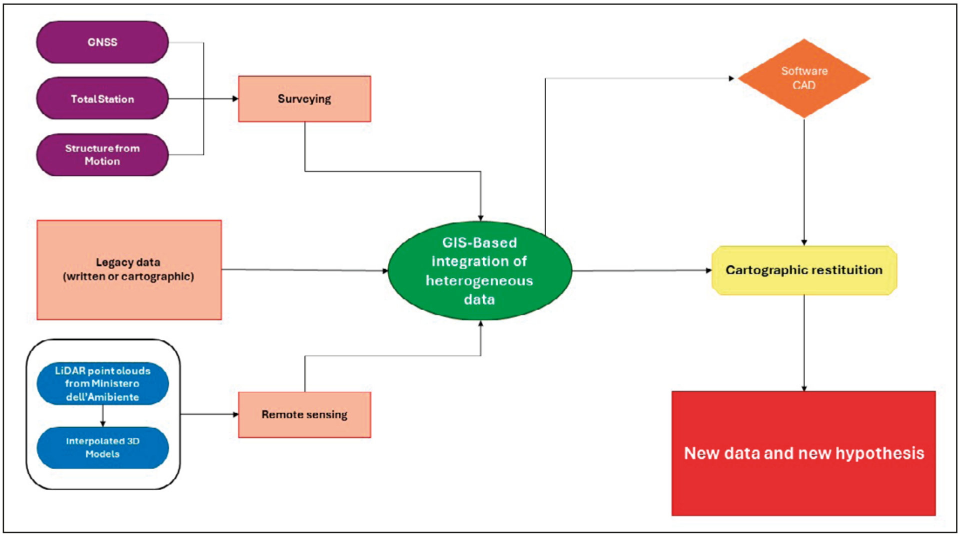

Fig. 1 – Diagram of the topographic data integration process.

84 / UTM 33N (EPSG: 32633) was adopted as the CRS (Coordinate Reference System). The cartographic base chosen is the Carta Tecnica Regionale (CTR) 1:10,000, produced in 2001 by the Sicilian Region (sections 646070, 646080, 646110 and 646120), imported as DXF. On the other hand, the IGM 1:25,000 maps (274 II-NO Belvedere; 274 II-SO Siracusa) and the 2019 orthophoto with a resolution of 20 cm/pix (same sections of CTR) produced by Agenzia per le Erogazioni in Agricoltura (AGEA) were added as Web Map Service (WMS) layers. The orthophoto provided crucial support, allowing for correcting the CTR's positioning errors, which were off by approximately 1 m to the W, using as a reference: 1) the monuments of the Neapolis Archaeological Park in Syracuse, which due to their lower height are less subject than other buildings to the distortion caused by orthorectification; 2) the measured Ground Control Points with GNSS.

2.2 *Reassessment of legacy data*

The aqueducts of Syracuse were first cartographically represented in 19th century. Among all other published data significant contributions on Syracusan aqueducts are Schubring 1865 and Cavallari, Holm 1883. For the first time, the aqueducts of Syracuse are cartographically represented. However, the first work uses as its basis *La corografia di Siracusa*, drawn up by Cavallari in 1839 during the years of his collaboration with D. Lo Faso Pietrasanta and published in the latter's work (Lo Faso Pietrasanta 1840,

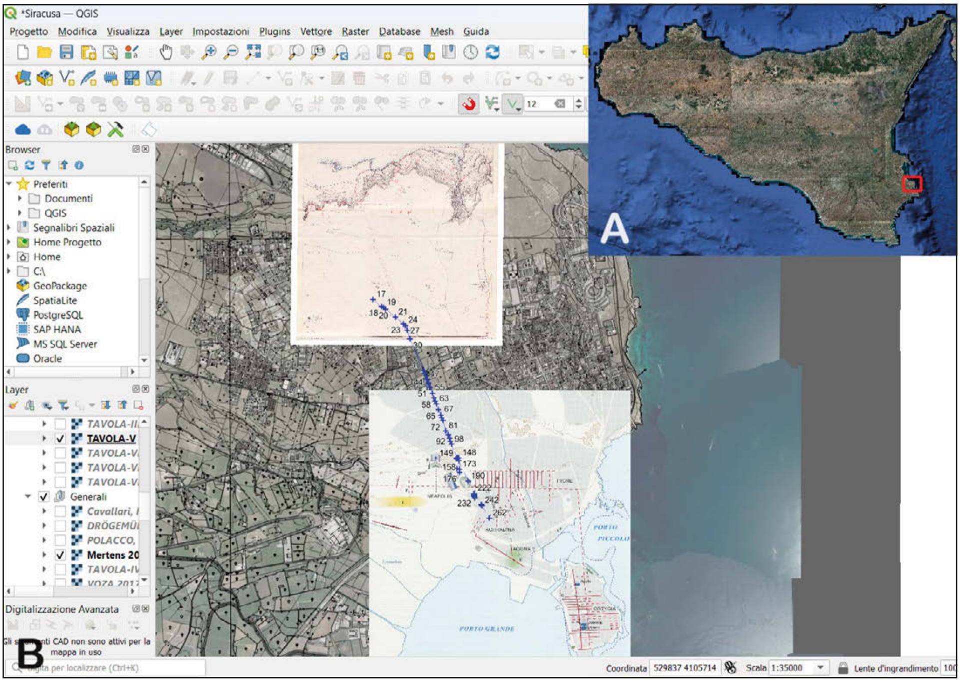

Fig. 2 – A) Orthophoto of Sicily. The red rectangle highlights the location of Syracuse on the East coast of the island; B) snapshoot of the QGIS software showing the Syracuse plateau area, illustrating the process of integrating and vectorizing the aqueduct path. In the background are Cavallari and Holm's Tab. V, D. Mertens' plan of Syracuse (Mertens 2006, 311, fig. 567), the CTR, and the orthophoto.

tab. 1). Although the best available at the time, it was not drawn geodetically and therefore cannot be directly used in a GIS environment. In the second one, however, F.S. Cavallari himself together with C. Cavallari, used as a basis for the archaeological map of Syracuse the detailed map drawn by the Stato Maggiore Italiano at a scale of 1:10,000 which is precise and accurate (Cavallari, Holm 1883, 12-13, tab. I-VII), then topographically reliable and easily imported into QGIS (Fig. 2). The two works are characterised by a substantial difference: the article *Die bewässerung von Syrakus*, although outdated in some of its theories, describes, and represents in detail for the first time, all hydraulic infrastructures (i.e. wells, canals, cisterns and basins) identified at the time in Syracuse; despite their cartographic representation, *Topografia Archeologica di Siracusa* actually devotes only a quite general chapter to Syracusan aqueducts instead.

More recent studies (Cultrera 1938; Gentili 1973; Guzzardi 1993-1994 e 2000; Filantropi 2022) have added further insights, including the discovery of an open channel covered by the Roman amphitheatre (Gentili 1973, 20-21) and a presumed stretch of the aqueduct in arches (Filantropi 2022). Then the aforementioned GIS was populated with all the geodata acquired from these studies, based on the topographical consistency of the graphic documentation, cadastral references and any other possible information regarding the location of the evidence described (Tortorici 2016). So, a geodatabase was designed to integrate legacy geodata with new data, enabling them to interact seamlessly. They, when possible, was positioned in GIS, through the 'georeferencer' tool, using homologous points visible between these, the IGM maps, the CTR and orthopotos. The evidence of archaeological interest was then vectorized: the route of the Acquedotto del Paradiso represented as a line and individual wells as point elements. Each vector was catalogued as a Unità Topografica (UT) with progressive number and other metadata as attributes: type, chronology, description, bibliography and measurements when available.

Thanks to a re-interpretation of Schubring's text, helped by the positioning of the Cavallari's tables, it was possible to locate, quite precisely, the evidence relating to the Paradise Aqueduct to which he refers, like wells not otherwise represented, including one that can be assumed to have been the well marking the beginning of the pipeline. Crucial support for Schubring's interpretation were the aerial photographs taken in the 1940s; georeferenced by homologous points too and when possible orthorectified, this process made it possible to recognise buildings referred to by Schubring, still visible in the Syracuse not yet affected by the great process of urbanisation that would take place in the following decades.

In this way, it was possible to visualise the route of the aqueduct in 2D (Fig. 3A), producing an archaeological map containing the complete catalogue of published data as well as new findings from the fieldwork. A total of 320 UTs were identified, of which 51 related to the Acquedotto del Paradiso.

2.3 *Re-interpolation and processing of LiDAR point clouds*

To enhance the available cartographic base and avoid being limited to a plan, a 3D model of the Syracuse plateau was created, from which a section of the route of the Aqueduct of Paradise including the new evidence was drawn; this was necessary not only to visualise the slopes but also to verify that the identified entities (51 UTs) were topographically and altimetrically related with the overall infrastructure. Therefore, it was necessary to reinterpolate the point clouds obtained from the LiDAR scans produced for the national topographic survey by the Ministero dell'Ambiente e Territorio, already been granted to the Laboratorio digitale di Topografia Archeologica of University of Naples (Brancato *et al.* in press; cf. also Fontana 2022). However, the

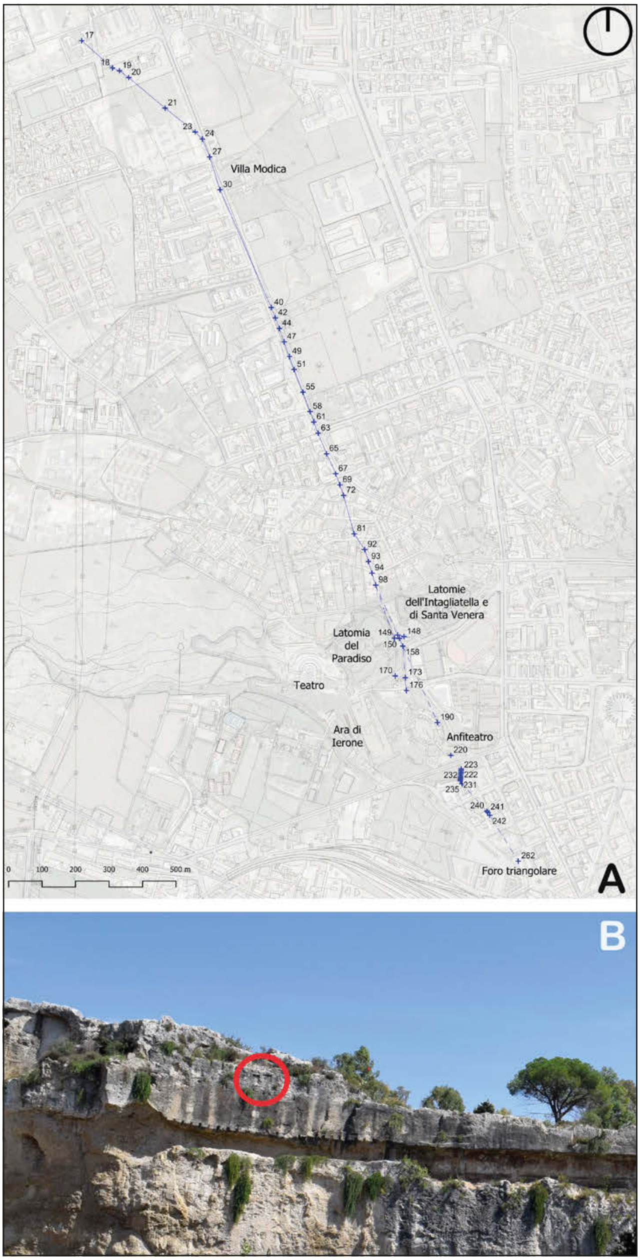

Fig. 3 – A) Reconstruction of the Acquedotto del Paradiso route through the related UTs; B) cut section of the aqueduct visible along the eastern boundary of the Latomia del Paradiso (UT 149). The red circle highlights the votive panels (courtesy of Parco archeologico e paesaggistico di Siracusa, Eloro, Villa del Tellaro e Akrai).

topographical exploitation of this type of dataset, is not so straightforward, since to date there is no single software that allows all the processing. Then, the use a series of software was required:

– LASTools 2.0.3, a suite of tools executable on QGIS;
– ConveRgo 2.05;
– Leica Cyclone 3DR 2023.00.01.42806, which unlike the others is proprietary and not open source.

Therefore, to facilitate the process, it is essential to know what features are to be inferred from the final model, and consequently the problems that will have to be addressed. Indeed, the point clouds, in fact, are supplied by the Ministero in the geographical reference system ETRF89 with ellipsoid height, in the form of ASCII text files. In the present case, since it was necessary to obtain a good model of the surface of Syracuse that could be imported into a GIS environment it was essential to carry these conversions: the format from ASCII to LAS, the CRS from geographic to cartographic WGS 84/UTM 33N and the elevation from ellipsoid to orthometric. Due to the scale and nature

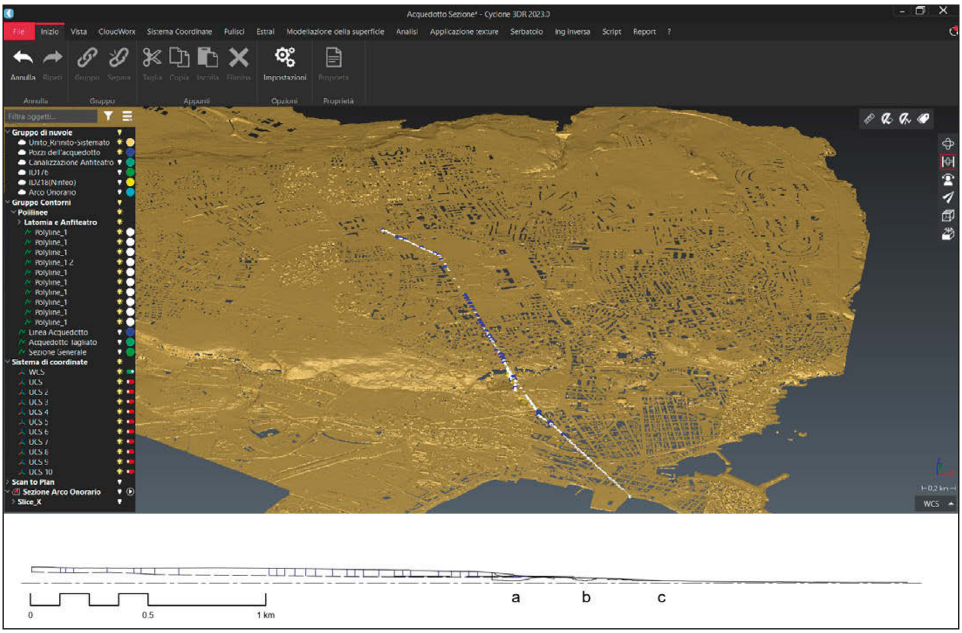

Fig. 4 – At the top, a snapshot from Leica Cyclone 3DR showing the interpolated point cloud of the Syracuse plateau, with the route of the Acquedotto del Paradiso in white and the wells in blue. Below, the section obtained in AutoCAD after completing the process: a) Latomia del Paradiso; b) Roman amphitheater; c) Foro triangolare.

of the study, it was crucial to obtain accurate and comparable elevation data, whether from GNSS measurements, CTR maps or published studies; other research utilizing LiDAR point clouds at a broader territorial scale, so does not face this issue (Fontana 2022).

The only free way to convert CRS and height is via ConveRgo, that still returns an ASCII text file that must be processed via LASTools' txt2las tool for obtaining a LAS file. In absence of the conversion grids, the positioning error on the X and Y axes, encountered in the GIS environment, was resolved by projecting the same point cloud, not processed by ConveRgo, through the las2las_project tool of LASTools, and thus obtaining two equal point clouds: one well positioned but with ellipsoid height and the other with orthometric height but poorly located. Through QGIS it was then possible to measure the distance between the two and with the 'las2las_transform' tool of LASTools move the second one. This produced a point cloud with geoid height positioned along the X and Y axes with centimetric error. The great potential of the LASTools suite lies in its ability to remove points relating to modern buildings and vegetation making possible to obtain a point cloud of the terrain only, in which the archaeological data is preserved, and, if necessary, to process the relative Digital Elevation Model (DEM), i.e. a 2.5D image of the terrain.

Obtained the point cloud of the terrain, it was possible to derive the section of the route of aqueduct. For this purpose, another software was essential: Leica Cyclone 3DR (Fig. 4). Although an open-source software capable of handling point clouds could have been used, the proprietary software was chosen because, despite its high specifications, it allows for fast and straightforward processing of point cloud sections; indeed, it is equipped with a tool, Scan to Plan, which makes it possible to 'slice' a point cloud, obtaining only the points that fall along the section line, and subsequently tracing them with a polyline exportable in DXF. In this way, even very large sections can be quickly produced. Since the path of the aqueduct is not completely straight, it was necessary to design no less than ten section lines, from which, using Scan to Plan, as many sections were obtained and after exported to AutoCAD. Thanks to that software the points relating to the aqueduct's evidence exported from QGIS were superimposed, and all the sections were merged in order to obtain a single frontal view.

From the visible sections of the canalisation and the wells whose depths are shown in the legacy data, the presumed line of the aqueduct canalisation was obtained, and for that it was also possible to hypothesise the depth of the unknown wells, as well as the height of the presumed pillars belonging to an overhead section. Considering that it is unclear where the aqueduct ended, it was decided to extend the section as far as the sea to have a visual comparison with the elevation of m 0 above sea level (Fig. 4).

2.4 *Autoptic analysis and surveying*

Direct observation and site survey were fundamental to the objectives of this research. Using methods and instruments of indirect survey (GNSS; TPS; UAV; Camera; SfM) it was possible to identify and, in most cases, detect evidence and structures related to the Acquedotto del Paradiso 'system'. Reference is made here to the new survey of a building that was most probably part of this system the so-called Piscina di San Nicolò ai cordari, an underground building in the Neapolis Archaeological Area of Syracuse (De Magistris 2014). The building, with a rectangular floor plan, is approximately 19.5 m long by 7 m wide and has a maximum height of approximately 5 m; it is also characterised by a roof composed of three-barrel vaults in *opus caementicium*, sustained by an entablature system using two flat arches, supported by two rows of seven square *opus quadratum* pillars. The new survey' results (Fig. 5) (Brancato *et al.* in preparation) which will be discussed later, have made it possible to identify phases of use related to the aqueduct.

In addition to this, during the explorations of the archaeological area, it was possible to identify what remains of the wells connected to the cut canal visible on the eastern boundary of the Latomia del Paradiso, and of votive panels located above these, at a very high elevation compared to the current ground level (Fig. 3B). Unfortunately, given their unreachability, it has only been possible to take photographs of them, and it is hoped to be able to survey them as soon as possible with the appropriate instruments;

Fig. 5 – New plan of the Piscina di San Nicolò ai Cordari and its surroundings. The red circle highlights the channel that fed the cistern. On the right, a detailed elevation view of that channel (courtesy of Parco archeologico e paesaggistico di Siracusa, Eloro, Villa del Tellaro e Akrai).

measurements have so far been taken from the 3D model. Instead, two wells were surveyed, afferent to the branch replacing the one that had been cut, two furrows afferent to a carriageway, passing exactly above the two wells, and the continuum of this canal that opens to the open sky. Finally, a well located behind the current ticket office of the area.

3. Results

3.1 *The route of the aqueduct*

Numerous scholars have traditionally identified only one construction phase for the Acquedotto del Paradiso: a rectangular canal approximately 1.80 m by ca. 0.5 m, dug into the geological stratum, without lining and connected to the surface by inspection shafts spaced about 25-30 m apart, with a total length of 1565 m (Cavallari, Holm 1883, 125-127). The comparison carried out in the GIS environment, of legacy and new data allowed this information to be updated. The positioning of 31 inspection wells, 12 of which were previously unidentified (Cavallari, Holm 1883, tab. IV-V), allows for the hypothesis that the aqueduct's path extends approximately 466 m further N. A relevant role was played by the three wells found near viale Scala Greca (Fig. 3A, n. 18-20) (Guzzardi 1993-1994) and the well reported by Schubring would seem to indicate the beginning of the conduction (Fig. 3A, n. 17) (Schubring 1864, 594-595, n. 110). The identification of the southern path of the aqueduct, however, is more complicated. Cavallari and Holm indefinitely indicate the end of the conduit near the open channel and the wells found on the limestone diaphragm between the latomie of Paradiso and Intagliatella. Recent studies (Collin Bouffier 1987, 683-687; Wilson 1990, 94-95, 2000, 13; Mirisola 2015, 55; Collin Bouffier 2020, 161-162; Filantropi 2022, 321), have reported that aqueduct main trench reached the Piscina di San Nicolò, deemed to be a cistern, or that from there the water reached the basin located in the centre of the Roman amphitheatre (Gentili 1973, 71-73).

Here, however, it is now necessary to focus on the open-air canal found on the eastern half of the amphitheatre in Syracuse (Gentili 1973, 20-21). This canal, characterised by a hydraulic coat 6-7 cm thick, consists of a cut in the limestone with a rectangular section 36-37 cm wide; these same technological and metrological characteristics can be found in the water conduit that fed the San Nicolò cistern (Fig. 5) and in the one, built on the diaphragm between the two latomie in place of the cut aqueduct already mentioned. Due to this data, it is possible to recognise a route with a total length of 2363 m heading S of the amphitheatre, in which interventions from several phases seem to be identifiable. S of this area, the city's water supply would also seem to be secured by a section of aqueduct on arches, corresponding to another phase of use, which would extend as far as the so-called Foro Triangolare, an area where the presence of warehouses and water-dependent production buildings has been hypothesized. According to this hypothesis, the Acquedotto del Paradiso would have reached a length of approximately 2843 m (Fig. 3A).

3.2 *A double gallery?*

The analysis of the now available section provided new evidence refuting the existence of the so-called double gallery in the three urban aqueducts of Syracuse. This uncommon technical feature, rarely attested elsewhere (Tölle-Kastenbein 1990, 68-72), would be present in all three Syracusan conduits; based on this assumption, it has allowed scholars to hypothesise a general project underlying their construction. Cavallari and Holm attest and verify the presence of this expedient in a single well (Fig. 2, n. 67) of the Paradise Aqueduct and hypothesise its presence along the entire route (Cavallari, Holm 1883, 126, tab. IV, n. 72bis). However, the section (Fig. 6, n. 67) suggests that the bottom of the identified well is too low to ensure a proper gradient for water flow to the open channel on the diaphragm between the two latomie, but not for the water flow to the channel cut in the latomia eastern edge. The higher position of the upper gallery, on the other hand, would seem to guarantee a good waterflow to the open channel. Therefore, as this technical solution is not attested for the wells further N, nor is any double gallery visible into the eastern edge of the Latomia del Paradiso, it is assumed that this may have been a technical feature to make the water to flow to the new canal excavated further E, built at a higher elevation than the original one.

3.3 *An aqueduct with several construction phases*

This new research identified a sequence of construction phases of the Acquedotto del Paradiso. According to rather recent discoveries, the construction of this system dates around the 4th century BC (Guzzardi 1993-1994, 1308-1309; 2000, 99-100), but the new survey of the Piscina di San Nicolò may reveal further chronological information. Initially, a road cut off in the limestone with a NE/SO direction was dug in the same area of the building (Brancato, Tortorici in press; Brancato *et al.* in preparation). Its continuation probably collapsed later together with part of the Paradise Aqueduct canal, which can still be seen in section in the eastern boundary of the latomia (Vitali *et al.* 2015, 56). The traces of the existence of this road axis can be observed from the presence of votive panels, now located at considerable heights along the eastern edge of the Latomia del Paradiso (Fig. 3B), which would have skirted the road axis similarly to the sides of the piscina. After the collapse of the latomia it was necessary, in order to re-functionalize the systems, to move both the road axis and the aqueduct canal to the east.

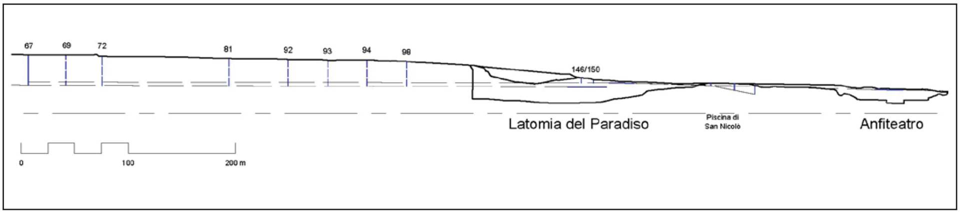

Fig. 6 – Section of the Acquedotto del Paradiso. Detail of the stretch passing through the Neapolis.

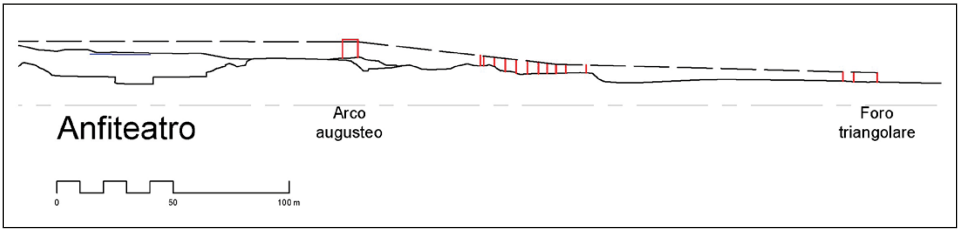

Fig. 7 – Section of the Acquedotto del Paradiso, detail. Hypothesis of an aqueduct stretch on arches. In red, Augustan arch and pillars.

This is evidenced by a roadway and two inspection pits in the centre of this, which indicate the existence of a canalisation that a little further S is revealed as an open canal. However, the construction techniques were different from before: the channels, often open, have a smaller rectangular section, and, above all, a hydraulic coating, like channel headed eastwards in front of the Casale Greco, the another directed to the Piscina di San Nicolò, and finally the last, probably the main one, that continued towards the amphitheatre, where the one oft-mentioned has been found, which, allows us to date it to before the construction of the Roman building, first century AD (Belvedere 1988, 353; 357). By comparing the results of the survey of the cistern with those of the aqueduct, it even seems possible to propose a phase of disuse between the first and second phase of use of the aqueduct, correlated with the building with a wooden roof that closed the sunken road that only later became a cistern with the channel. This phase of disuse would fit in well with the progressive abandonment that characterise the N of the Neapolis and with the sudden cessation of use of the baths of via Zappalà (Cultrera 1938) both datable towards the end of the 3rd century BCE, close to the Roman conquest (Basile 2012, 213). It is unclear when the aqueduct was restored, but certainly before the 1st century AD.

The aqueduct headed S towards an area in need of water supply, probably that of the so-called Foro Triangolare: however, after the construction of the amphitheatre there is no evidence of regarding its reconstruction (Brancato, Tortorici in press). A series of pillars has recently been identified as possible piers arches of the aqueduct' arches (Filantropi 2022). However, this hypothesis brings with it several problems. To avoid the amphitheatre and connect to the pre-existing canal without increasing its length, the new conduit would necessarily have had to pass near the Augustan arch (Gentili 1951, 277). However, if we accept this hypothesis, the aqueduct would have had to pass in front of the honorary arch. On the other hand, maybe the honorary arch itself was one of the arches of the aqueduct (Fig. 7), similarly to the Porta Prenestina-Labicana, or Porta Maggiore, in Rome (Ashby, Richmond 1935, 81-82, 141-144, 242-244; Coarelli 1980, 15-16). In this case, the passage through the honorary arch would involve that the pillars to be about 6 m: indeed, it is possible to hypothesize a section of the aqueduct on arches that would be able to maintain the overall slope consistent with that of the general infrastructure. However, the excavation of the area did not bring to light other pillars aligned to the aforementioned ones (Gentili 1951, 261, 264, fig. 1, 3). Nevertheless, it remains certain that in this area the water flows and the greatest clue is the nymphaeum to the S of the amphitheatre (Fig. 3A, n. 220; Fig. 7).

4. Conclusions

The integration of heterogeneous geodata within a GIS environment (Brancato *et al.* 2023) may significantly enhance our understanding of the Acquedotto del Paradiso and the ancient topography of Syracuse. By combining legacy data, historical cartography, 3D models from LiDAR point clouds and SfM, and direct surveys, this study has uncovered a complex and multi-phased history of the aqueduct previously not recognized. The research highlights the value of a multidisciplinary approach, blending traditional archaeological methods with advanced digital tools to provide a more nuanced and accurate depiction of ancient water supply systems. The results not only may refine our knowledge on the aqueduct's path in early imperial age, but also suggest the possibility of previously unknown phases and challenge theories such that of the double gallery. This project may be a model for future studies in the archaeological topography of ancient supply systems of Syracuse, demonstrating how GIS and digital technologies can reinterpret historical data and yield new insights into ancient urban planning and their infrastructures.

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ABSTRACT

This study explores the GIS legacy data integration for a reassessment of the archaeological topography of Syracuse, with a focus on the Acquedotto del Paradiso. The research updates the understanding of Syracuse's ancient waterscape by combining traditional archaeological methods with advanced digital technologies. Legacy data, historical maps, and recent fieldwork were systematically integrated into a GIS software, enhancing the spatial analysis and re-evaluation of the aqueduct's route and construction phases. The study incorporated topographical bases, LiDAR point clouds, and autoptic analyses, revealing new insights into the aqueduct's structural phases, including potential multi-phase construction and a double gallery system. The integration of these diverse datasets not only refined the known path of the aqueduct but also provided a detailed 2D and 3D visualization of it. This multidisciplinary approach emphasises the importance of combining traditional and modern techniques to improve the accuracy of archaeological topography, offering a more comprehensive understanding of ancient urban water supply systems in Syracuse.