Integration of remote sensing and GIS for archaeological investigations

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Abstract, The western hinterland of the modern city of Istanbul contains some of the most remarkable monuments of ancient and medieval hydraulic engineering dating from the fourth to the twelfth centuries AD, including lines of aqueduct channels and bridges extending up to 336 km to the west of the modern city. Until recently fieldwork has been limited and only within the last two decades have there been serious attempts to map the complexity of the monuments and water lines. The dense forest which covers much of the northern hills of Thrace is a major factor restricting fieldwork and survey, yet at the same time the woodland ensures the preservation of much of the system. Two previous studies of the water supply system have been able to identify the major spring sources, to map the line of the water supply channels and to record and locate over sixty bridges which are a key component of the system. However these studies have been constrained as they are not able to integrate adequately this survey data. The new research programme between Istanbul Technical University (ITU) and Edinburgh University commenced in 2007 and includes all existing GPS data and archaeological observations to be incorporated as part of a modern GIS combining the topographical and hydraulic information available from 1:25 000 digital maps with a wide range of high and medium resolution remotely sensed data. Further surface GPS based archaeological survey has been undertaken over the past two years and has been able document a significant number of the extant channels and bridges. Using high resolution IKONOS images and orthophotos it has been possible to create a textured land surface of forests and fields for the Thracian digital surface model (DSM) in which to situate the various monuments and channels of the water supply system. This digital resource is now capable of providing the basis for future archaeological documentation and analysis and two case studies are given. Integrated with multi-spectral data this gives the opportunity to view the system in its wider setting and also to identify major urban and landscape changes impacting on the long-term conservation and management of the ancient remains.

1. Introduction

The new city of Constantinople (mod. Istanbul) was founded in AD 324 and throughout late antiquity and the middle ages it was the greatest city in Europe, admired and coveted by both Moslems and Crusaders. With a few notable exceptions most of the Byzantine city has been lost or buried beneath the Ottoman and modern Turkish conurbation and archaeologists and historians face the challenge of reconstructing the urban history from fragmentary remains and often ambiguous texts. One of the greatest, but least recognized, monuments of the Roman and Byzantine city was the long distance water supply created for the new city from the fourth century AD. The clearest representation of this great system within the city is the Bozdogan Kemer, a fourth-century Roman aqueduct nearly one kilometre in length, together with over 150 cisterns ranging in size from the open air cistern of Asper to the covered Basilica Cistern and the scores of smaller cisterns throughout the old city. These elements of the water supply within the city have been recognized since the sixteenth century. But unlike the old city of Rome much less is known outside of the walls of Istanbul where there has been little research.

Pioneering research was carried out by the late Prof. Cecen from ITU, Turkey who initiated a research programme in 1991. In the early 1990s he turned his attentions to the Byzantine water supply system outside the city. His research for the first time presented clear evidence for the extent of the water channels and bridges including colour air photographs of some of the major bridges at Kursunlugerme and Kumarlidere. In 1994 an archaeological team from Newcastle University, UK, led by Prof. James Crow began a programme of research concerned with recording and mapping the Anastasian Wall, a 56 km long wall stretching across the Thracian peninsula from the Black Sea southwards and dating from the sixth century AD. The line of the wall crosses at right angles the furthest extension of the aqueduct channels and these were included as part of the landscape survey project. From 2001 the Newcastle team were able to carry out a more detailed archaeological study of the water supply system (Crow *et al*. 2008). This fieldwork ended in 2005, but in 2007 a further stage of research was begun with a collaborative programme between ITU (Prof.Derya Maktav) and Edinburgh University (Prof.James Crow) funded by TUBITAK (Turkish Science and Technical Research Council*)* and with support from the British Academy.

The aim of this second phase is to investigate the application of the integration of remote sensing and GIS for a fuller understanding of the archaeology, topography and the hydrology of the Water Supply System.

2. Study area

The study area is located immediately to the west of the expanding city of Istanbul and includes the three provinces of Istanbul, Tekirdag and Kirklareli. The maximum area of study extends 250 km as far as Vize (Kirklareli) to the west and the distance from the Black Sea to the Marmara Sea varies between 50 to 100 km. A notable feature of the region is the deeply forested hills of northern Thrace flanking the Black Sea coast. The approximate geographic coordinates of the study area are *longditude:* 27°.647562, *longditude:* 28°.993192, *latitude:* 41°.638505, *latitude:* 41°.006197 (Figure 1).

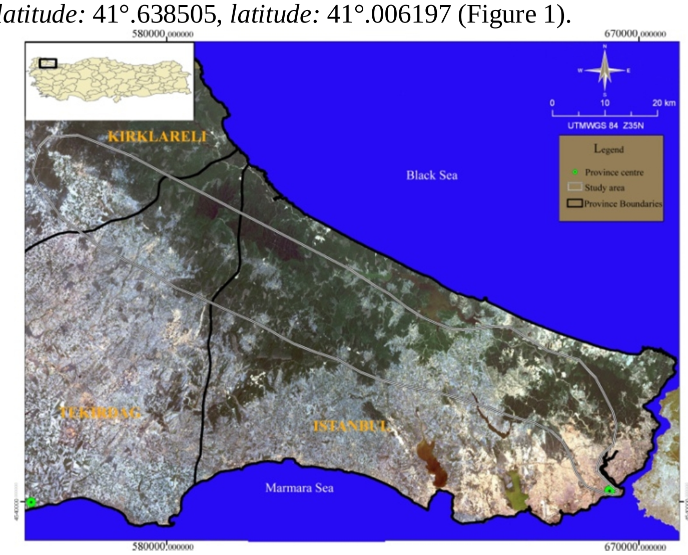

Figure 1. The study area: Thrace, Turkey.

3. Data and methodology used

The available data comprise the results of archaeological field survey and GPS measurements, different resolution satellite imageries, classified satellite imageries, orthophotos, and 1: 25 000 digital topographical maps. The methodologies used included mosaicing of the satellite imageries and supervised techniques for the classification of the satellite imageries. Within a GIS it was possible to drape the processed satellite imageries and/or orthophotos of differing scales over the DSM which was obtained from 1:25 000 topographical maps (Maktav, *et al.* 2008).

4. Archaeological field survey

The full extent of the water supply was estimated by Prof. Cecen at 240 km and for much of this length it snakes around the heavily wooded Stranja hills of northern Thrace. Further estimates (Crow *et al*. 2008) suggest that the total length of the longest channel was significantly longer, achieving a maximum length of 336 km, with other channels at 225 km. Although this extensive forest is regularly harvested for firewood and the production of charcoal, in many places it is dense like a jungle and presents particular and unusual problems for any archaeological survey since the best preserved elements are often the most inaccessible. The water supply system outside the city comprises three main components:

- water sources at springs,
- vaulted channels cut into the hillsides, ranging from 0.60 m to 1.60 m in width and between 1.60 to 2.20 m in height,
- aqueduct bridges which carry the channel across low ground and valleys, some of these are amongst the most monumental aqueducts in the Roman world, with widths of 135 m and rising nearly 40 m in height.

To understand the system it is necessary to combine an appreciation of the topography and archaeology in the context of a detailed large-scale cartographic record. Prof. Cecen was able to use maps at a scale of 1: 50 000 and he relied on both the local knowledge of villagers and also helicopter survey of some of the densest regions. He was concerned above all to identify the approximate course of the system and to illustrate the main bridges presenting these on an outline map at a scale of 1: 50 000 (Cecen, 1996).

The Newcastle survey (Crow *et al*. 2008) which commenced a few years later was initially limited to identifying and describing the monuments and line of the system. Limited use was made of GPS in 1995 demonstrating the technology's ability to map the line of the water channels in forested areas around Kursunlugerme. From 1998 a GPS system with a base station was employed to identify the line and elevation of the channels, demonstrating for the first time that the additional line from Danamandira village was part of the overall system. This equipment provided excellent accuracy but was of restricted use in wooded areas and from 2000 onwards a hand-held GPS was employed to identify specific points along the channels and bridges. At the same time it was possible to gain access to a set of mid-twentieth century 1:25 000 maps based on detailed Ottoman originals created between 1912-15. The line of the water channels and the positions of the bridges have been located using the GPS data and other existing map information. To provide the topographical context for the channels and bridges the scanned Ottoman map base has provided contours for the new maps of the water supply system presented in the recent monograph (Crow *et al*. 2008). These in turn complement the detailed archaeological descriptions of the channels and the major bridges from which it has been possible to construct a detailed structural history of the development and maintenance of the system from source to points of delivery within the Byzantine city. As an example, the survey and elevation of the bridges at Kursunlugerme and Balligerme are shown in Figure 2.

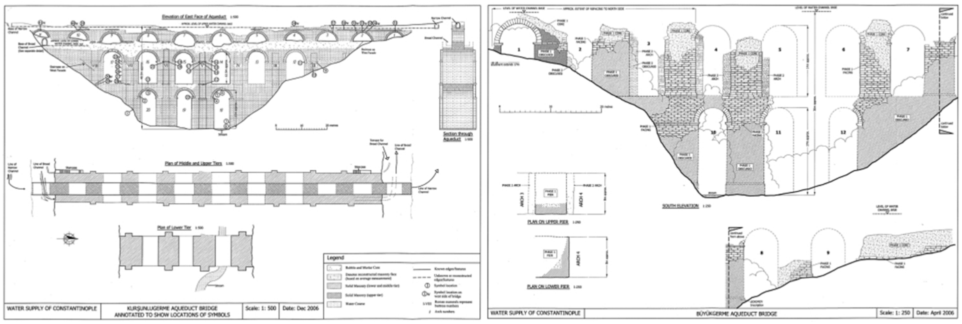

Figure 2. Archaeological field survey at Kursunlugerme and Balligerme aqueduct bridges (Crow *et al.* 2008).

The Newcastle survey however was limited by the absence of a digital map base which in turn restricted the implementation of a GIS of the entire water supply. A consequence of the collaboration with the remote sensing scientists from ITU has ensured that the initial aims can now be achieved and through the use of satellite imagery it is now possible to develop still further the study of the landscapes and the long-term management of these internationally important archaeological monuments.

5. Remote sensing

Remote sensing technologies provided the opportunity to achieve a synoptic view of the entire system from sources to the points of delivery in the city. Furthermore the use of high-resolution data ensured that potentially it would be possible to identify elements of the water supply system and associated features. In addition it has been possible to monitor land-use and land-cover information using multi-spectral data. From this evidence it has been possible to understand and interpret the effects of these changes for the survival and identification of these archaeological remains (Beck, A. et al. 2007). Recent advances in remote sensing include LIDAR, a high precision measurement tool that has many uses in forest management (Renslow 2000; Harmon *et al., 2006*; Doneus and Briese 2006; Crow et al. 2007) also provide the opportunity to discover archaeological features obscured by less dense forest and vegetation cover. This methodology has not been available for this study.

Satellite data have included LANDSAT (1975, 1987, 2000) and IKONOS (2006). LANDSAT data has been used to study land-use and land-cover classification and has demonstrated very clearly the increase advance of the urban area into the countryside of Thrace with negative implications for the survival and future study of the archaeological remains. Another major feature which this study has revealed has been the extensive increase of quarries for gravel and cement manufacturing across northern Thrace with particular impact on the eastern line of the water supply line (Figure 3). Comparing the supervised classified LANDSAT imageries for the years 1975, 1987 and 2000 clearly show the land use changes in the vicinity of the Alibeyköy district (Figure 3). The first difference is the extansion of urban areas (red) increase (Maktav, D. et al. 2005a,b). The second is the increase in the number of quarries and cement factories (white) as a result of the intensive construction activities in the city. The investigation of the classified LANDSAT imageries dated 1975 and 1987 demonstrates the increase of quarries (white) west of Alibeyköy Dam and of the urban areas (red) south of the dam. The expansion of quarries and urban areas has adversley effected the water supply system and in many places the line has been damaged and/or lost beneath these quarries and urban areas.

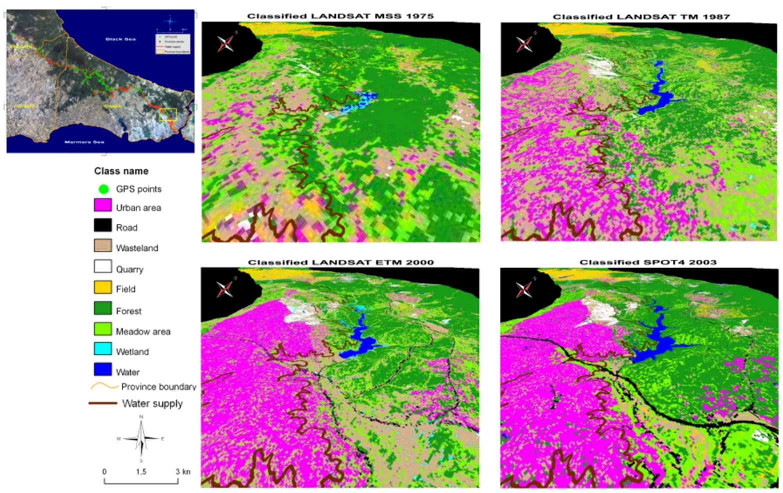

Figure 3. 1975, 1987 and 2000 LANDSAT imageries (supervised classified) draped over DSM.

From the IKONOS pan-sharpened data, with less than 1 m ground resolution, it has been possible to locate the major monuments but also from the observable variation in the forest cover to trace in places the line of the water supply channels and the location of the less well-known bridges. The results of this digital image processing have been tested by ground truthing. For the precise location and mapping of the water channels a handheld 12 channel Trimble Navigation GeoXT GPS receiver has been employed. This was found to have considerable advantages over previous GPS systems employed by the Newcastle team which were either accurate but difficult to apply in the forested areas, or lacked the resolution the GeoXT provides.

6. Hydrology

The volume and flow of the water in discrete catchments relating to the system are calculated using ArcHydro GIS software (Figure 7). The results will be announced later in the final report of the ongoing project. This provides a better understanding of the potential discharge of the river systems and their contribution to the water supply system. For hydrologic applications, DSM of the study area was obtained with a grid interval of 10m by using 1: 25 000 scale digital topographic data. ArcHydro was used to predict drainage from DSM. The higher the DSM precision, the more realistic the rivers are; otherwise, large flat areas will produce an unnatural drainage network (Maidment 2002). Once the DSM was selected, the high and low points on the DSM were corrected in order to eliminate interruption of the river network (Tarboton and Bras *et. al*. 1991; Figure5). The filled DSM data was used to generate flow directions (Figure 5). The D8 method was used to determine natural flow directions. There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is commonly referred to as an eight direction (D8) flow model and follows an approach presented in Jenson and Domingue 1988. The direction of flow is determined by finding the direction of steepest descent, or maximum drop, from each cell. The distance is determined between cell centers (Akar 2008). Another model generated by using DSM in hydrologic studies is the flow accumulation model obtained from the flow direction model (Figure 5). Water flow directions are identified from DSM and a water flow directions model is created accordingly. Starting from the top right corner on the water flow directions model, the flow accumulation values are calculated cell by cell. Each grid cell (pixel) on the DSM has a numeric value. If a cell does not receive a flow from another cell, its value will be zero (Figure 6). The flow from the cell can only be to one neighbouring cell with a lower altitude value. There are eight possible directions for each cell. Figure 7 shows the possible flow directions from cell 50 and the values to be assigned to cell 50 in the new water flow direction model.

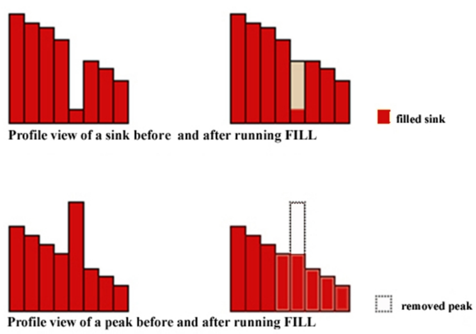

Figure 4. Editing peaks and sinks in DSM.

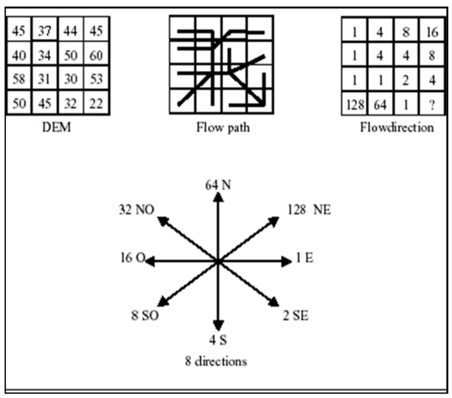

Figure 5. Calculation method of flow direction.

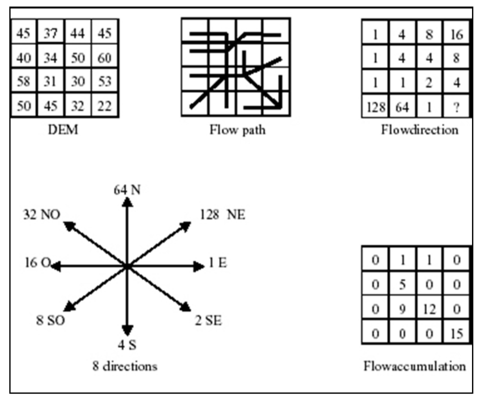

Figure 6. Calculation method of flow accumulation.

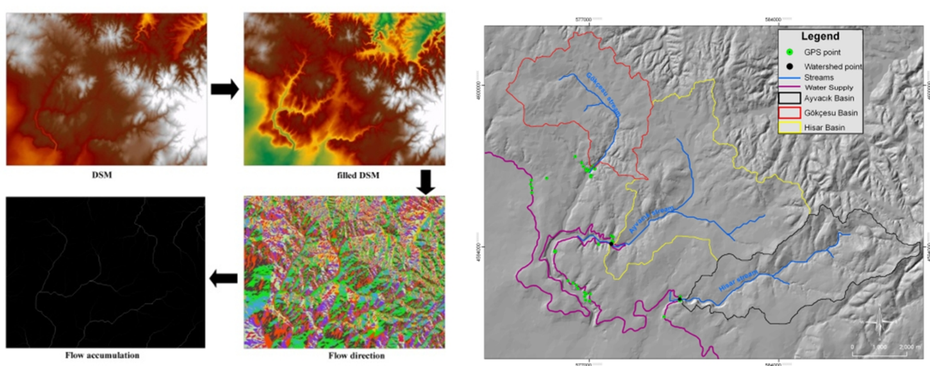

Figure7. Steps of the stream which is generated from the DSM.

6. GIS

Until now it has not been possible to integrate the results of the archaeological surveys within a GIS based on a detailed digital DSM. A consequence of the availability of the DSM data has been to ensure the integration of archaeological survey data, photographs and other records with the wide range of remotely sensed data as noted before (Figure 8). Information about details of vector and other data are stored as an attribute in tables with a range of values, subtypes and domain areas (Figure 9).

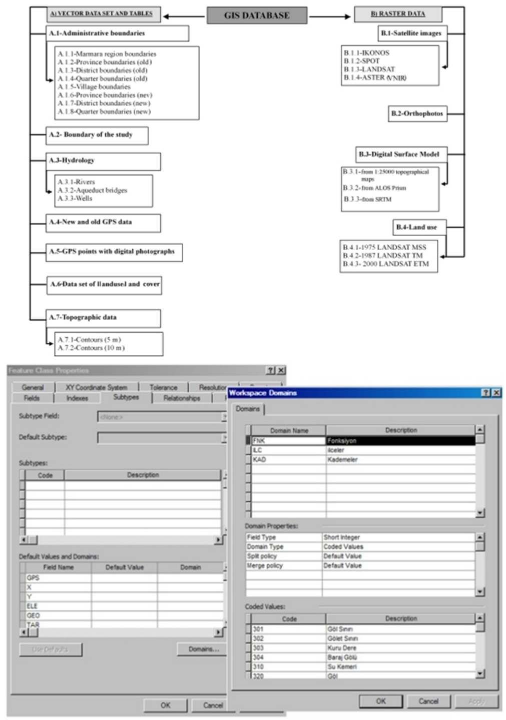

Figure 8. Layers of GIS and composition of subtype and domain.

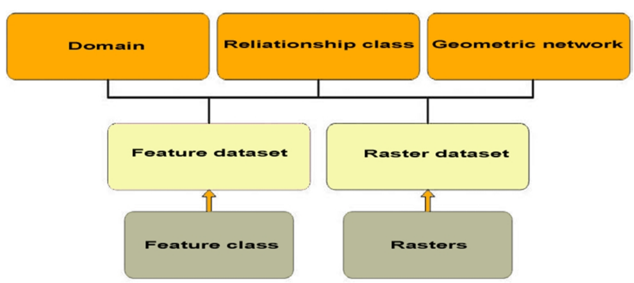

Figure 9: General structure of database.

Roman Water Supply Line was determined with using fieldwork, GPS measurements and high resolution satellite images (Figure 10). Also, to determine the line was used DSM and contour.

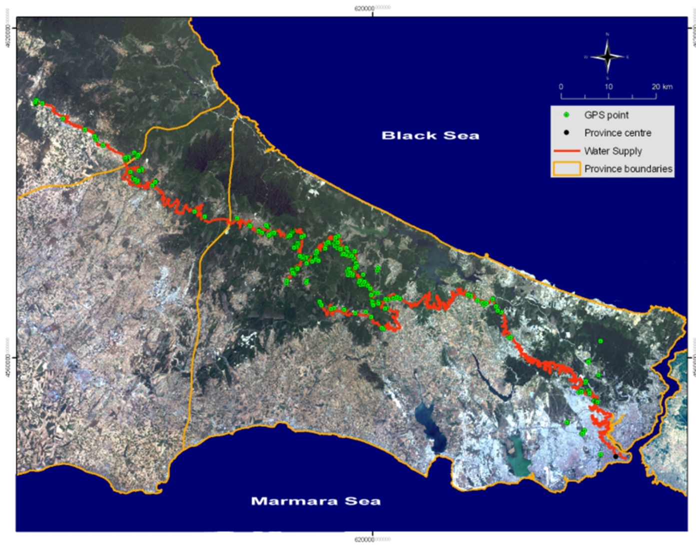

Figure 10: Water suppley system.

9. Conclusion

The application of remotely sensed data has ensured that the ancient water supply system is understood not a series of individual sites which is frequently the case in previous fieldwork, but has been unable to provide a synoptic view of the entire system. Prof Cecen's approach was to define the extent of the line of the entire system but through the application of remote sensing and GPS survey based on a robust DSM and integrated within a comprehensive GIS, we have been able for the first time to achieve the requirements of both archaeological enquiry and heritage and landscape conservation. The combination of high resolution satellite images with the up-to-date digital map base has created a textured land surface of forests and fields for the Thracian DSM. From the archaeological survey the location of the bridges and the water channels may be identified from known points and predicted using specific GIS tools. However in addition the ability to view the forest cover and recognise differential patterns of growth which frequently mark the location of major bridges has been of great benefit in recognising the monuments.

A second component of the project has been the combination of multi-spectral data with high spatial resolution data. This approach has ensured that it has been possible to both provide detailed ground information relating to the archaeology of the system, such as aqueduct bridges, but also to understand the how the wider landscape changes, such as quarries, forests and urban expansion impact on the recognition and survival of the system.

Furthermore, unlike other aerial surveys, such as photography, other techniques such as LIDAR have the potential to see through the deciduous woodland and can be used for further archaeological investigations. Computer processing can filter the LIDAR data to effectively remove the reflections from the canopy and allow a ground surface to be modelled potentially revealing archaeological earthworks that have never been previously been recorded in aerial photographs.

Acknowledgements

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