

Dynamic Models to Reconstruct Ancient Landscapes

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In this paper a method of landscape analysis is demonstrated through raster-based digital elevation models (DEM) using the case-study of the Helike Delta, Gulf of Corinth, Greece. In the Classical Period, Helike was the seat of the Achaean League and the worship centre of the god Helikonian Poseidon. With the focus on the earthquake and tsunami of 373BC, DEMs are generated using dynamic models of sea level rise, tectonic and pulse tectonic uplift, subsidence, and sediment deposition. Starting with a DEM from the present day landscape, simulated DEM models are generated for the Early Helladic II/III (2500-2100BC), Classical (480-323BC), Hellenistic (323-146 BC), and Roman (1st Century BC – 4th Century AD Periods). The models shed light on archaeological interpretation concerning the continuity and discontinuity of human occupation in the Helike Delta. Moreover, the method demonstrates a new approach to dynamic landscape analysis using GIS that is general and can be applied to any landscape.

Keywords: GIS, dynamic models, raster-based DEM, landscape analysis, geomorphology, geoarchaeology, Helike Delta

1. Introduction

The Helike Delta is one of the most seismically active regions of Greece. The Eliki fault is a 22km long normal fault consisting of two collinear segments of 9 and 13km separated by a step-over or transfer zone (KOUKOUVELAS *et al.*, 2001, 2005). The transfer zone causes the two segments to behave independently during seismic events and having separate effects on the topography of the Delta such as changing the courses of the local rivers (POULIMENOS and DOUSOS, 1996). Seismic and aseismic tectonic uplift are continuously raising the mountains together with the Delta. During periods of aseismic uplift high energy sediment deposition from the rivers causes rapid progradation of the Delta and, at major earthquakes, the entire plain to the north of the fault experiences abrupt subsidence causing agradation of the Delta with marine transgression at lower elevations, soil liquefaction and submarine landslides (SOTER *et al.*, 2001). This pattern of continuously changing shoreline, which also depends on the rate of sea level rise, is characteristic of the Holocene and it affects other regions of the Gulf as well and it has been well documented in ancient literature.

The complex archaeological stratigraphy of the Delta is thus a consequence of earthquakes with co-seismic tectonic uplift, aseismic tectonic uplift, uneven

subsidence, soil liquefaction, flood debris flow, colluvial and alluvial sediment deposition, terrestrial and marine landslides, and seismic sea waves. Stratigraphy can change abruptly in only a few metres resulting in a landscape difficult to unravel, but one that offers interesting and challenging questions.

The main research question addressed in this paper is related to the understanding of the geomorphology of the Helike Delta from the Early Helladic to the Roman Periods and how these factors have influenced the continuity and discontinuity of landscape occupation. Geographic Information Systems (GIS) based dynamic models are proposed and validated by extensive borehole, environmental and excavation data, and cross-validated against archaeological and literary sources. Related research questions are concerned with generating and testing models of tsunami reach, and the interpretation of ancient written sources concerned with the earthquake and tsunami of 373BC.

Related previous work using modelling techniques in connection with a GIS include CLELAND *et al.* (2008) on Native American use of recessional shorelines over a 700 year period. The models use a variety of environmental data including geology, hydrology, biology and archaeology resulting in distribution maps plotted over the period and used both for analysis and validation. The work of NUNEZ, VIKKULA and

KIRKINEN (1995) explores shoreline modelling in an isostatic uplifting region of Finland. A raster-based DEM approach estimates past elevations as a function of time and the only variable considered is isostatic uplift enabling the establishment of a relationship between ancient site location and shoreline. GILLINGS (1995) describes a model of flood dynamics in the Tisza Valley, Hungary. Supported by borehole data, a DEM model was used to simulate past environments and fluvial behaviour and the relationship to cultural activity leading to new hypotheses of land exploitation and raising interesting questions to be tested with independent data. SMITH (1995) has demonstrated how GIS can support broad based studies of ancient landscapes in Greece and how these can be validated by and linked to written sources. It was established that in Classical Greece all minting activities occurred at lower elevations; also, the interpretation of Pausanias acquired a new dimension concerning spatial relationships between locations and writing sequences.

The research discussed above uses GIS in three distinct and discrete ways:

1. The use of a variety of environmental, geological and archaeological data to validate models of sea-land relationships;
2. The use of a dynamic model applied to a current DEM where a geological variable (tectonic uplift) is used to generate past environments; and
3. The use of ancient writings to guide analysis and interpretation of DEM based models.

It is here argued for a comprehensive approach to landscape analysis using GIS. The method proposed here integrates the three approaches above into a single framework. A case study of the Helike Delta landscape is modelled for the Early Helladic, Classical, Hellenistic, and Roman Periods. It is shown that DEM dynamic models supported by detailed geological quantification and validated by environmental and archaeological data and ancient written sources can effectively be used for landscape analysis.

This paper is organized as follows. Section 2 outlines the proposed methodology. Section 3 describes a particular way of acquiring a DEM through remote sensing. Section 4 describes the proposed dynamic model, Section 5 presents simulation results and a conclusion is given in Section 6.

2. Methodology

In order to reconstruct and validate ancient landscape models a four-step methodology is proposed:

1. Acquisition of a DEM model. This paper focuses on a method of acquiring data through remote sensing;
2. Identification of relevant time-dependent seismological and geological variables and models

from current literature. The purpose is to use such models to modify elevation values in the DEM, where each modified DEM is a snapshot of an ancient landscape;

3. Generation of raster-based DEM models for the events and/or periods of interest for which archaeological evidence and historical records are available;
4. Plotting of all relevant environmental, archaeological and other data on the raster-based DEM. This will lead to well-grounded interpretation and to both validated models and methodology.

Some important considerations concerning the above steps are as follows. First of all, in step 1 DEMs can be purchased or downloaded in a variety of formats. In order to be able to apply the dynamic models to elevation data, it is necessary to have access to the actual data (i.e. to the numbers representing the heights of each point). If the acquired DEM is formatted for a particular application say, MapInfo, it needs to be exported as plain ASCII organized into a matrix of rows and columns.

Secondly, a raster image (e.g. bmp, jpeg, or tiff formats) of an aerial photograph needs to be acquired, for example through Google Earth, corresponding exactly to the area specified by the DEM data matrix. The number of pixels in the raster image is normally much larger than the number of elevation data readings and a correspondence must be established between how many pixels would map to a single elevation point.

Thirdly, the identification of time-dependent seismological and geological variables obviously depends on the particular environment under study, and here we offer a general model that can be simplified as required. In the case study of the Helike Delta, the geological models used are the ones proposed by SOTER (1998) and SOTER and KATSONOPOULOU (1999). The method assumes that we start from a present day DEM model overlaid by a raster image. As new DEMs are calculated for past environments, their corresponding raster images must also change, that is, all elevations at or below sea level correspond to blue pixels while all other pixels remain unchanged. This allows us to visualize the sea advance/retreat in relation to land.

3. DEM Acquisition

Elevation data acquired by NASA Shuttle Radar Topographic Mission (SRTM) are accessible via the Consultative Group for International Agriculture Research (CGIAR, 2008). SRTM data are available as 3 arc second (approximately 90m horizontal resolution) DEMs split up into tiles of 5x5 degrees. The difficulty of such large data files for this project is slow display as 99% of the data are irrelevant for the selected area in the

Helike plain as it covers only approximately 0.050x0.036 degrees. Attempts to crop the selected area from the large tile proved to be cumbersome and prone to errors.

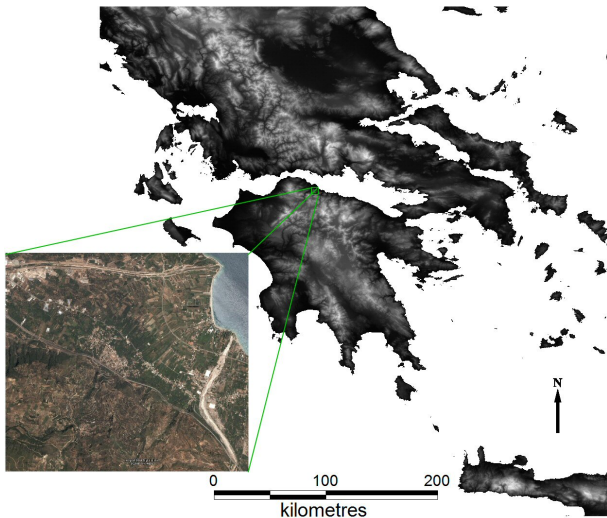


Figure 1: Background (map): a single tile of SRTM elevation data covers most of Greece. Foreground (image): the selected area on Google Earth for elevation readings.

However, Google Earth (GE) 4.1 interface uses the same SRTM 90m data in their elevation models with the added advantage of being sub-tiled into smaller area grids (GOOGLE EARTH, 2008). Thus, a feasible solution although very laborious, was to acquire the model by first selecting the region of interest on GE, approximately 17km² (Figure 1) and then directly performing elevation readings – a total of 28,341 readings were taken forming a matrix of data with 141 rows and 201 columns. This data was geo-referenced as prescribed by MapInfo and imported as a DEM using Vertical Mapper. A generated model using TIN at 1m contour interval is depicted in Figure 2.

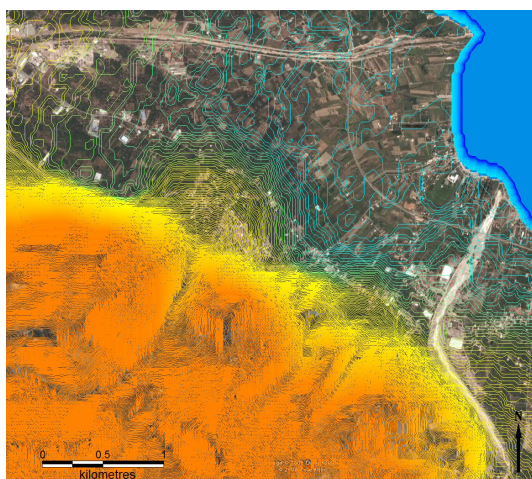


Figure 2: TIN model overlaid on the raster image.

4. Dynamic Models

SOTER (1998) studied a number of time-dependent geological variables and proposed detailed quantification of these for the Gulf of Corinth for the Holocene Era. The quantification considered in this paper focuses, and is only valid for, the period between 4300BP to present day. The quantified variables are:

1. The *rate of sea level rise* (R_S), expressed in metres per thousand years mky^{-1}
2. The *rate of vertical tectonic uplift* (R_U) relative to the local sea level, in mky^{-1}
3. The *pulse tectonic uplift* (U) in m,
4. *Subsidence* (S) at the event or earthquake considered in m, and
5. The *rate of sediment deposition* (R_D) in mky^{-1}

The quantification of each of these variables in relation to the Helike Delta is as follows. Concerning sea level rise, the global eustatic sea level is determined by the amount of glacial ice. As global sea levels change, local isostatic adjustments happen. Soter has adopted the eustatic sea level curves as published by Peltier (SOTER 1998) which show a deceleration of sea level rise in 7000BP and a cessation of global melting at around 5000BP and applied local adjustments for the Gulf of Corinth following the work of Lambeck (SOTER 1998). The ‘corrected’ local sea level curves show an average sea level rise $R_S=0.5mky^{-1}$ over the past 5000 years.

In order to define the rate of tectonic uplift in relation to the local sea level, it is useful to consider that sea level does not change over time and that the only movement is due to tectonic uplift. In this case sea level is the baseline reference frame and if we could mark the position where a hypothetical cliff coincides with the sea, over time the cliff would move upwards at a certain rate (expressed in metres per thousand years). However, it must be noted that the relationship between variable sea level rise and tectonic uplift is very complex as both rise independently at variable speeds. While it is safe to assume a constant rate of sea level rise, the same does not apply for tectonic uplift. In reality, the rate over the baseline reference frame discussed above is not linear in time, but is punctuated with earthquake related discontinuities with periods of relatively steady aseismic trajectory.

SOTER (1998) has analysed the age of 21 relic shorelines in an attempt to determine the changes in tectonic uplift in relation to the local corrected sea level. Samples were dated using the uranium-series method and carbon dating calibrated for the local ‘reservoir effect’: local surrounding limestone mountains continuously discharge carbon depleted in C14 into the Gulf which has limited exchange of water with the Ionian Sea. These are then taken up and metabolized by aquatic organisms and deposited as C14-depleted

organic sediments. An additional correction of 380 years was found necessary and thus applied to all marine carbon date ages in the Helike Delta.

By plotting the calibrated age of the shoreline against elevation, Soter has shown that about 9000BP the shoreline was 20m lower than it is today. Moreover, two major discontinuities were observed at 7000BP and 2300BP. The first discontinuity implies a pulse tectonic uplift of about 6-7m while the second, which coincides with the earthquake of 373BC, is set to $U=2.0\text{m}$. In the earthquake of 1861AD, a pulse tectonic uplift $U=1.0\text{m}$ is assumed. Moreover, evidence suggests an earthquake in 2300BC (ALVAREZ-ZARIKIAN *et al.*, 2008) perhaps of lower magnitude than in 373BC and this does not show in the sparse data. Careful analysis of the plotted shoreline data allows us to conjecture a discontinuity in 4300BP with a pulse tectonic uplift $U=2.0\text{m}$. By the same token, aseismic tectonic uplift should assume two different rates: $R_U = 0.9\text{mky}^{-1}$ between 4300-2300BP and from 2300BP to present a rate of $R_U = 2.0\text{mky}^{-1}$.

On earthquakes occurring on a normal fault, pulse tectonic uplift is normally accompanied by subsidence of the hanging wall block. Usually, subsidence is larger than pulse tectonic uplift and in the case of the Eliki Fault, this causes marine transgression that drowns parts of the delta surface. This clearly happened in the earthquake of 1861AD as described by Schmidt (KATSONOPOULOU and SOTER 1998); (SOTER and KATSONOPOULOU, 1999; 2005) where a subsidence $S=2.0\text{m}$ is reported. Soter's (1998) analysis of borehole samples for the event of 373BC yields inconclusive results showing co-seismic subsidence of the order of 9m, 6m and 4m although he points out that it does not take into account other factors such as pulse uplift and subsidence in the intervening earthquakes between 373BC and 1861AD, nor soil compaction or differential deposition. Taking Soter's analysis into account, it is assumed here a subsidence of $S=4.5\text{m}$ in 373BC and $S=4.0\text{m}$ for the lower magnitude of the earthquake of 2300BC.

Finally the deposition rate is considered with SOTER (1998) suggesting an average of 16.8m in the last 7000 years (2.4mky^{-1}). It is clear that deposition has a strong localized effect with periods of faster deposition followed by a steady flow of sediments. Also, until around 50 years ago when riverbank walls were built, the two local rivers were continuously changing course. Archaeological data was used to guide quantification of deposition rates, in particular, at the Early Helladic site (situated right in the middle of the plain between the two rivers) where archaeological data imply a rate of about 1.0mky^{-1} over the past 4300 years. Thus, it is assumed here a rate of sediment deposition $R_D=1.0\text{mky}^{-1}$ from 7000-2300BP and $R_D=3.0\text{mky}^{-1}$ from 2300BP to present. It is also acknowledged that the rate can be much higher on locations nearer the riverbeds but such effects are not to be included in the current model.

Once the rates are quantified, the method to generate a DEM of a past environment proposed here involves updating the height or elevation of every cell in the DEM by simple multiplication and addition over the desired time span. It is important to stress that we are interested in the relationship between sea and land so we need to consider which variables have a plus effect, that is, a raising of land, and which variables have a minus effect, that is, a lowering of land in relation to sea level.

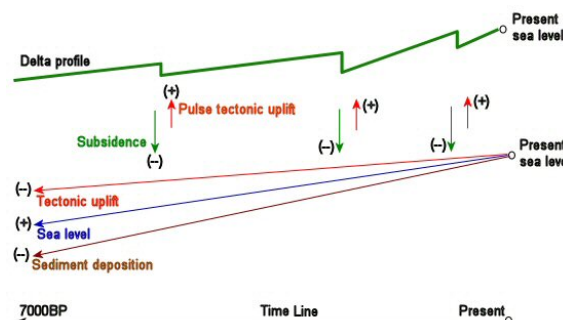


Figure 3: The Helike Delta elevation profile (on top, not to scale) over the past 7000 years with the variables' effects plus (+) or minus (-) on current DEM heights.

Figure 3 depicts the effects of each variable in the Helike Delta. Starting at "Present sea level" on the right of the picture, back in time is to the left. Tectonic uplift raises the tectonic plate and in the past any point in the Delta was lower than it is today, so the *rate of vertical tectonic uplift* (R_U) has a minus effect (i.e. it is subtracted) from all current DEM heights. Since sediment deposition is always adding layers of soil over time and any point was lower in the past than it is today, the *rate of sediment deposition* (R_D) also has a minus effect and needs to be subtracted from all current DEM heights as we travel back in time.

The rise in sea levels deserves careful consideration. Since it is known that in the past sea levels were lower than the present day, it means that any point in today's DEM is higher in relation to past sea level, so the *rate of sea level rise* (R_S) is added to DEM heights to represent this relative rise. Pulse tectonic uplift and subsidence only happen during the event of major earthquakes and, as discussed earlier, *pulse tectonic uplift* (U) raises the plate and must be added while *subsidence* (S) lowers the plate and must be subtracted.

Combining these time-dependent variables into a single expression where time is given in BP yields:

$$H_{t1} = H_{t0} + (S_{t1} - U_{t1}) - R_U^{*t} - R_D^{*t} + R_S^{*t} + M$$

Where t_0 and t_1 are the start and end time of the simulation, t is the time span of the simulation given by $t = (t_1 - t_0)/1000$ as this is expressed in ky^{-1} , and H is the height in metres of every single point in the DEM at time t_0 (initial) and t_1 (final or updated).

The last term of the equation M refers to any other relevant *modelled* variable. It is included here as the proposed method is general; variables are included or

excluded depending on the characteristics of the landscape under analysis. Examples of M would be soil erosion over time, tilting of tectonic plate, marine landslide causing localized subsidence at the shore, other localized subsidence or deposition and indeed, any other local or global effect that can be described over time or as a pulse event. If M is included, the correct sign (+/-) needs to be determined following similar reasoning as above. In the simulations described in the next section M is zero and thus, excluded.

In the equation above, normally $(t_1 - t_0) > 0$, that is, the simulation is run back in time. If a simulation is required to run forward in time say, from 4300—2373BP, where $t_0 = 4300$ and $t_1 = 2373$, then $(t_1 - t_0)$ is negative and the inverse is performed: subsidence and sea levels are subtracted while tectonic uplift (seismic and aseismic) and deposition are added.

5. Simulation Results

A number of raster based DEM models were generated starting from the present day landscape to AD1861 then to the Early Helladic (2300BC). From there, the models run forward in time to the Classical, Hellenistic and Roman Periods (Figure 4):

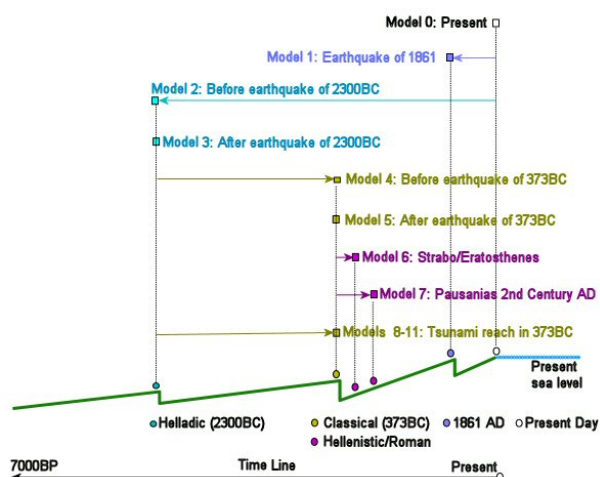


Figure 4: Twelve landscape models are generated.

- Model 0: the acquired DEM model of the present day landscape,
- Model 1: from present to the earthquake of AD1861, validated against Schmidt's account,
- Model 2: from present to before the earthquake of c.2300BC,
- Model 3: immediately after the earthquake of c. 2300BC,
- Model 4: from the earthquake of c.2300BC to before the earthquake of 373BC,
- Model 5: immediately after the earthquake of 373BC,
- Model 6: from the earthquake of 373BC to the account by Strabo / Eratosthenes 150 years later,

- Model 7: from the earthquake of 373BC to the account of Pausanias in the 2nd Century AD,

- Models 8-11: tsunami reach in 373BC compared to the accounts of written sources.

All models are validated and interpreted using written sources, archaeological and environmental data from boreholes and excavations, and a number of geophysical surveys. Data is available from a total of 99 boreholes plus 77 trenches and trial trenches across the plain.

5.1. Environmental and Archaeological Validation

Models 0 and 1 are validation models. Since a raster image is overlain on each DEM and all heights with a value of zero or negative should be painted blue in the raster image, then the shoreline of Model 0 should exactly correspond to the present day shoreline, this was verified. References are available for the earthquake of AD1861 mainly based on the work of Schmidt published in 1862, reported here in (KATSONOPOULOU and SOTER, 1998; SOTER and KATSONOPOULOU 1999). Schmidt described the event and produced drawings of the aftermath showing a submerged strip of 200m from the seashore probably caused by a marine landslide. He suggested that a similar event but of greater magnitude destroyed Helike in 373BC. Therefore, after calculating the DEM heights for Model 1 in AD1861, all points within 200m of the shore were forced to a negative value in the DEM and the same method was then applied to the seashore after the earthquakes of 2300BC and 373BC.

The models for c. 2300BC (Figures 5 and 6) are fully consistent with archaeological and environmental data. Figure 5 shows a landscape simulation before the earthquake: all the evidence found concerning the Early Helladic is in trenches H7, 21, 22, and borehole B75 with archaeological excavations revealing foundation walls of EHII/III "corridor houses" and associated pottery. Furthermore the archaeological evidence indicates that this site was at the sea side which is confirmed by the dynamic model showing exactly that.

In B58 ceramics dating to 2300BC were recovered from sandy clay at a depth of 3.0 - 4.20m and above that is further environmental evidence showing a brackish environment with ostracods together with evidence of a tsunami (ALVAREZ-ZARIKIAN *et al.*, 2008). The interpretation is that the Early Helladic settlement was placed close to the shore and the earthquake of 2300BC destroyed and subsided the site, which then became a marine environment (Figure 6). In H7 where Early Helladic occupation has been found, there is evidence for a marine environment indicating that the area has experienced long term submergence. As silting continued over the next centuries, the connection to the sea was cut off and the area became a lagoonal environment, which then turned to marsh by the Classical Period.

Furthermore, the long-term submergence could explain the hiatus in the archaeological record in the mid-plain of almost 1000 years from the Early Helladic Period. Occupation is evidenced again towards the end of the Mycenaean and Proto-geometric periods in the southeast of the Delta, away from the mid-plain.

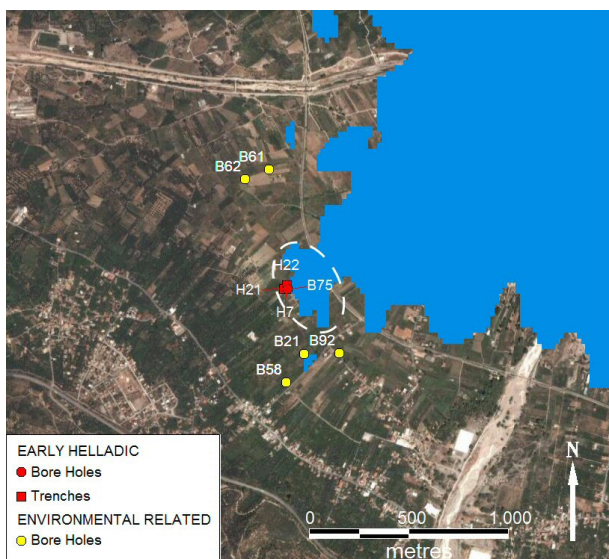


Figure 5: 2300BC before the earthquake.

The generated models for the Classical Period (Figures 7 and 8), where all evidence of Archaic/Classical Period occupation is overlaid on the raster-based DEM, show that before the earthquake of 373BC the shoreline was close to the current railway line (Figure 7). Near trench H8 it indicates a possible lagoon in the same place as in the model of c. 2300BC near B58. The interpretation is that this is more likely to have been a swampy area in 373BC; in fact the whole area is known as “the swamps” even today.

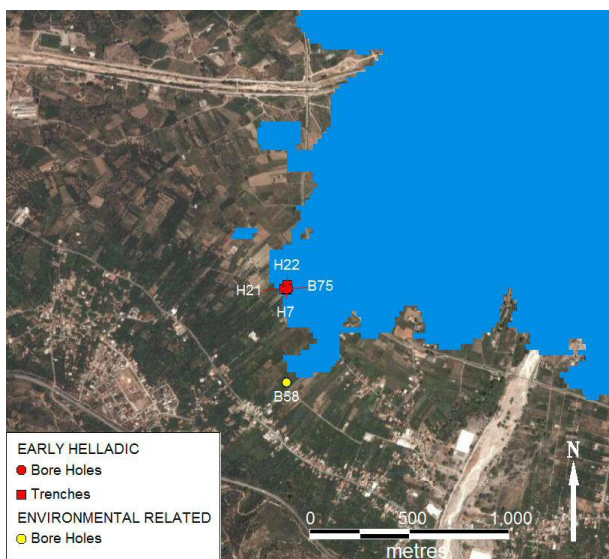


Figure 6: 2300BC after the earthquake.

The model after the earthquake of 373BC is depicted in Figure 8 and shows large areas being submerged when compared to the model before the earthquake. The area

in the centre of the picture (where the sea advances most inland) indicates submergence and the formation of a lagoon. Trenches H10, H18 and H19 revealed Classical pottery and remains of walls at 3.0-3.3m depth with one in H19 destroyed and fallen towards the sea, suggesting the backlash of a tsunami according to Soter (KATSONOPOULOU, 2005). Also, H10, H18 and H19 showed a brackish environment with ostracods below the walls reinforcing the earlier interpretation of marine, lagoonal and marshy environments at that location.

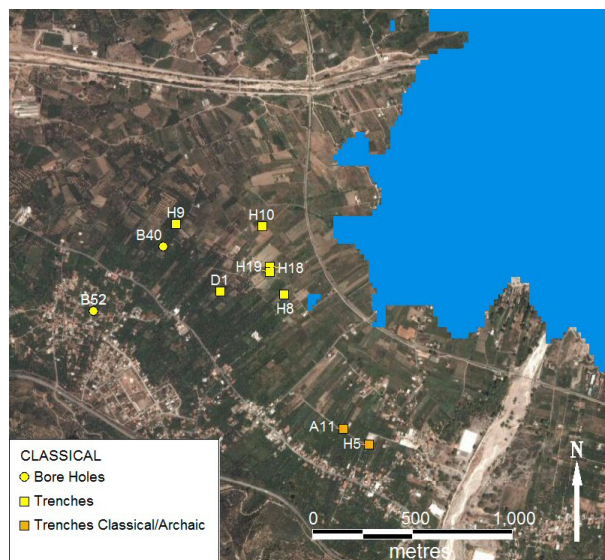


Figure 7: 373BC before the earthquake.

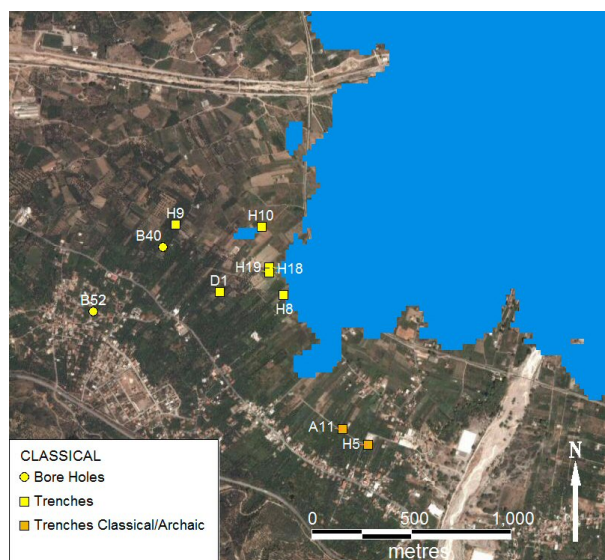


Figure 8: 373BC after the earthquake.

A DEM model was generated and compared with the accounts of Eratosthenes (*in Strabo, App., le*), 3rd Century BC, approximately 150 years after the events of 373BC. Eratosthenes reports that the bronze statue of Poseidon was in the *poros* (normally a narrow passage of water in ancient Greek). KATSONOPOULOU (2005) has reinterpreted this as an inland marine lagoon, which is consistent with the environmental data and its

possible location can be inferred from the DEM model and is annotated in Figure 9.

Figure 9 depicts a DEM model showing a possible scenario in the 2nd Century AD, which was compared with the accounts of Pausanias. By this time the area in the centre of the bay was silted over and a Roman road ran through it. Pausanias may have travelled along this road and he reported that the ruins of Helike were still visible under water. The model suggests that such ruins may have been under a marine lagoon, formed in the same location as the ancient lagoon of c. 2300BC and this view is further reinforced by extensive gravity measurements in the area by DIMITROPOULOUS and NOUTSIS (2005) whose results closely match both the location and orientation of the lagoon as indicated on Figure 9.

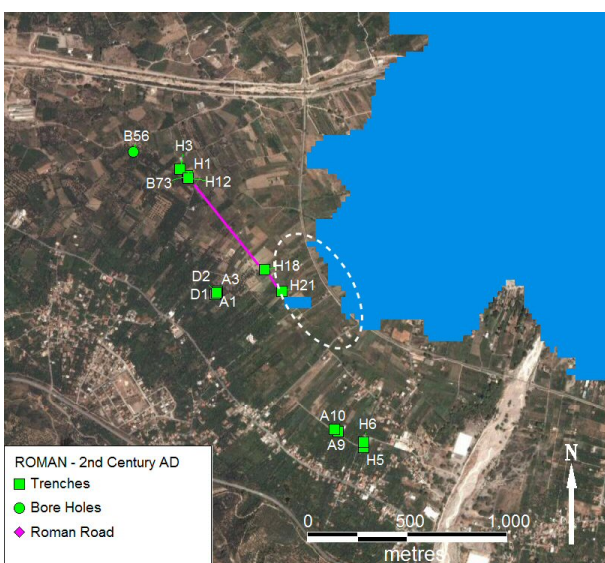


Figure 9: Pausanias' account in the 2nd Century AD.

5.2. Models of Tsunami Reach

The earthquake and tsunami of 373BC were reported by a large number of ancient writers and this rich historical record allows us to test models of tsunami reach and whether it is likely or not that the entire city of Helike was destroyed. A tsunami following the earthquake is reported by Herakleides, Theophrastos, Eratosthenes, Poseidippos of Pella, Aelian, Diodoros, Strabo, Ovid, and Pausanias among others (KATSONOPOULOU, 2005). The records do not conflict too much but they do differ in the magnitude and destructive consequences of the tsunami. The contemporaries to the event, Herakleides and Theophrastos, provide a description of the topography by stating that the city was located on a higher ground and that the entire area was covered by seawater.

Strabo, Diodoros, Pausanias, and Poseidippos all reported that the magnitude of the earthquake was of the most destructive kind and as a result the sea was raised to a great height and the people disappeared together with their land. Two writers had actually visited Helike:

Eratosthenes who reported that ferrymen told him that the bronze statue of Poseidon holding a hippocampus stood under water and was dangerous to those fishing with nets; and Pausanias who reported that the ruins of Helike were under water and heavily deteriorated.

There is archaeological evidence for the events of 373BC, particularly the tsunami, from four trenches, H1, 7, 9 and 19, and three boreholes, B58, 62, and 73. While it is unknown the extent of the tsunami reach, the minimum scenario is that it reached the surface heights of those horizons showing Classical occupation and with evidence of the tsunami itself; this was calculated to be a wave of 10m and is shown in Figure 10. Many more models were generated at increasing wave height intervals, and a tsunami height of 40m was necessary to flood the remaining Classical horizon in borehole B52.

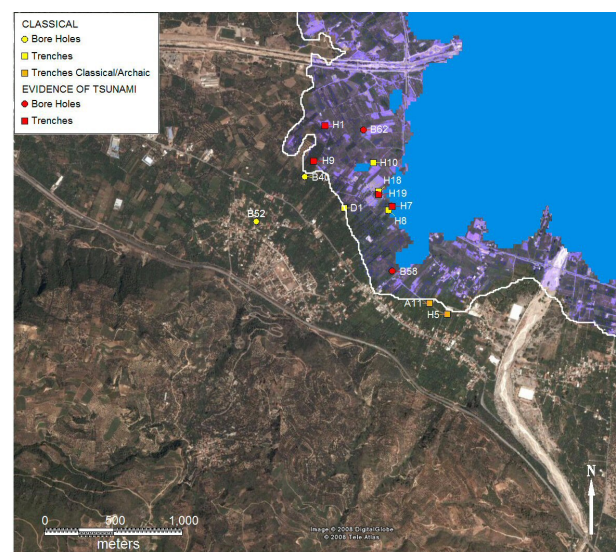


Figure 10: Tsunami reach of 10m.

It is interesting that Pausanias states that the tsunami “encircled the city” and if one assumes that a good proportion of the people lived on higher ground as suggested by some ancient writers, and as is the case today, then the 40m tsunami model is plausible even though this seems very unlikely. The models suggest that the tsunami reached a maximum of 10m and thus did not destroy all of Classical Helike and that the evidence for total destruction is not conclusive. The models show that such claims may have been exaggerated as has been previously pointed out by SOTER (2001) and others.

For most of its inhabitants to have perished, ancient Helike must have been more densely populated at lower elevations compared to today's pattern. A note of caution is that the elevation model may differ substantially to the reality of 373BC and many factors have not been considered such as the magnitude of the marine landslide that contributed to the wave generation, the actual size of the wave, the forces involved, or wave attenuation as it hit obstacles limiting actual reach on land.

Conclusion

The dynamic modelling method described in this paper allows a way into the story of the Helike Delta at different temporal levels and at scales ranging from microfaunal identification and absolute dating to large-scale spatial considerations allowing archaeological interpretation of long term trends, sequences and changes. Moreover, the model is generic and other variables can be added as required and the methodology can be applied to any dynamic landscape modelling and analysis.

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