



# Investigation of the physical-geographical characteristics of river delta with geophysical and satellite data. The case study of Pineios River, Greece <sup>☆</sup>



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## ABSTRACT

This paper presents the methodology of an applied geophysical and remote sensing research at river deltas for their subsurface and surface structure and its application in the deltaic plain of Pineios River (Thessaly, Greece). The scope is to primarily calculate the thickness of deltaic post alpine deposits, with the contribution of Transient Electromagnetic Method (TEM), but also identify the surficial characteristics (biotic/ abiotic) of the area with the appropriate combination of spectral bands and spectral indices. Regarding the remote sensing approach, some geomorphological features were outlined. This was managed from six false color composites of the area, produced by combining spectral bands and additional five false color composites by combining several spectral indices.

- The results of the TEM method along with their statistical analysis provided important information regarding the spatial distribution and thickness of the lithological units along the deltaic plain.
- The combination of spectral bands 8, 7, 6 seems to adumbrate the hydrographic network of the area and even detects possible changes in the inflow.
- The combination of spectral indices MSAVI2, WV-BI, WV-WI was helpful enough to geomorphological mapping of the deltaic plain.

<sup>☆</sup> **Related research article:** Dilalos S., Alexopoulos J.D., Vassilakis Em., Poulos S.E. (2022). Investigation of the structural control of a deltaic valley with geophysical methods. The case study of Pineios river delta (Thessaly, Greece), *Journal of Applied Geophysics*, 202, 104652, <https://doi.org/10.1016/j.jappgeo.2022.104652>

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## Specifications table

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Resource availability:	Equipment: WalkTEM Software: ViewTEM, ERDAS Imagine and ArcGIS Pro (ESRI software) Software: ViewTEM, ERDAS Imagine and ArcGIS Pro (ESRI software) WorldView-2 satellite images

## Method details

## Introduction

More than half a billion people live on or close to deltas, often in large cities [1–2]. There are numerous advantages for societal development established by the existence of Deltas, such as a smooth topography, available fresh resources, good transportation via waterways and the nearby coast, productive soils for agriculture, and a valuable biodiversity and recreational value through, such as beaches, wetland ecosystems and coastal forests [3]. Potential threats such as sea level rise and subsidence come from both environmental change but also human intervention [2]. Taking into account that sea level rise, sand depletion, groundwater pumping and human pressure on delta land are expected to increase, conventional approaches to control delta landscapes may become unsustainable [4]. The determination of the subsurface geological structure is crucial for modeling the paleo-relief where the river delta has been created on, but also allows the delineation of the river's flow paths [5].

Remote sensing techniques in combination with field data and Geographic Information Systems (GIS) have been used in various agricultural applications or research [6–9]. With the accessibility of global remote sensing databases, the physical attributes of deltaic systems are becoming increasingly better quantified [10–14]. Geophysical surveys have been conducted in many deltaic regions and coastal zones around the world [15–22].

Regarding the presented case study of Pineios river, the authors have already discussed the results and the interpretation from the application of several geophysical studies, including the Vertical Electrical Soundings (VES), the Transient Electromagnetic Soundings (TEM) and gravity measurements [23–27].

## Study area

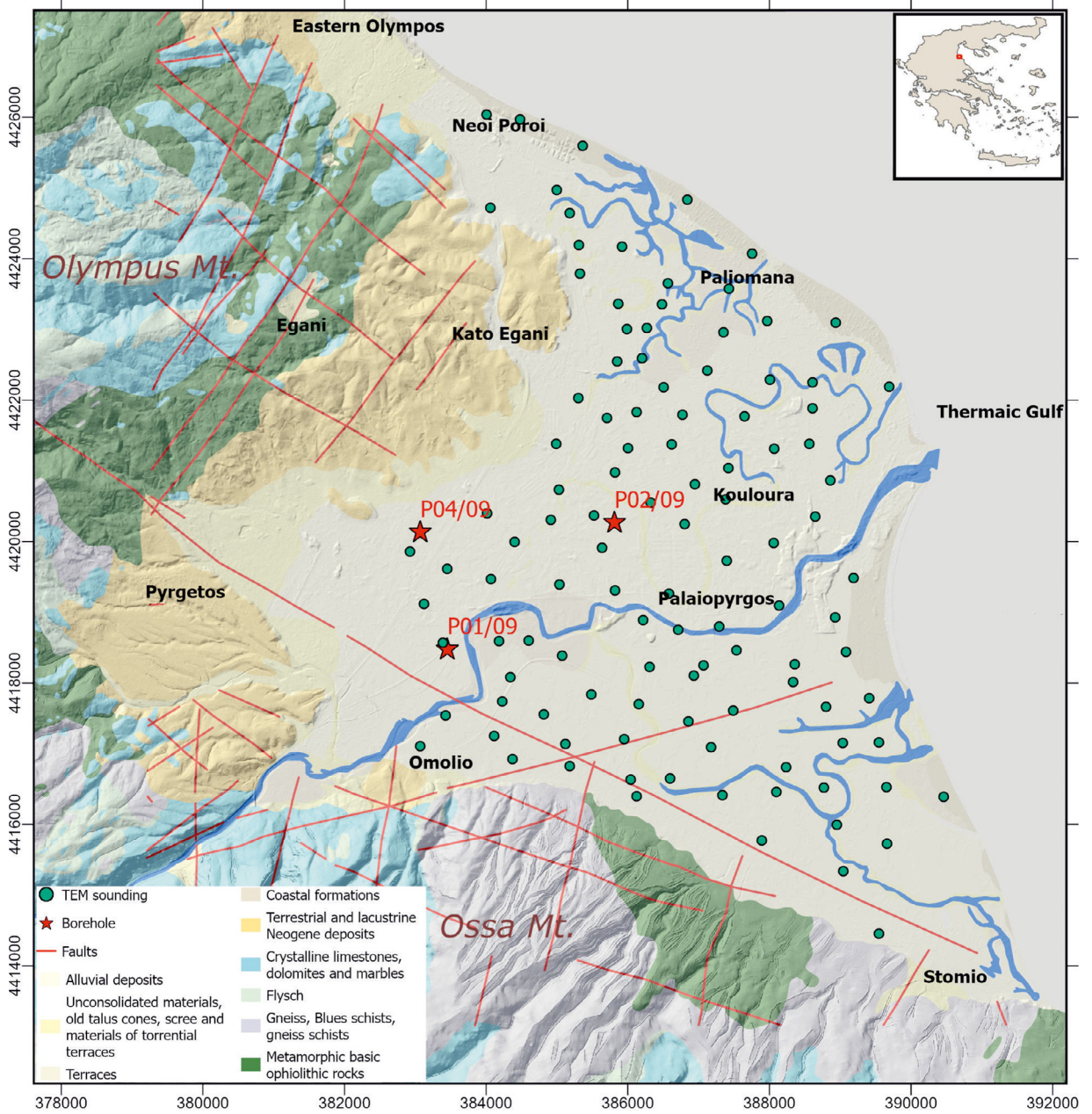
Pineios River is the largest Greek river with its drainage basin within the Greek borders. It is also the only river in Greece with reduced flow control (in only less than 10% of its catchment) [28]. Its delta has been recognized as an environmentally sensitive coastal zone protected by the NATURA 2000 network (RAMSAR convention). It is characterized by great fresh surface water availability supporting a valuable biodiversity of fauna and flora [29]. It includes an estuary with riparian woodland, riparian forests marshes, freshwater lakes, coastal zones and sand dunes. The delta of Pineios River is characterized by the expanding touristic exploitation of the coastline and the extensive agricultural cultivation [30–31].

The relief of the deltaic plain is flat and incorporates meanders, radial riverbeds and isolated parts of old riverbeds, which function mainly during flood events, revealing the continuous geomorphological evolution of the plain over the years [32]. In Fig. 1, the coverage of the largest part of the deltaic plain by alluvial sediments is obvious, while sand dunes and coastal sediments exist along coastal areas. The northern (Olympus Mt.) and western (Pyrgetos alluvial fan) boundaries of the deltaic plain comprise Neogene deposits (conglomerates and marls) and Pleistocene formations (scree, debris cones and fluvial terraces). The southern margin (Ossa Mt.) is surrounded by metamorphic rocks, such as dolomites, crystalline limestones, marbles, shales, gneisses, blue schists and ophiolites [33]. Based on the authors of [34] the Neogene formations have undergone severe tectonic deformation leading to several block rotations with values of 10–30°, towards south. The NW dipping normal fault zone located south of Omolio settlement strikes WSW-ENE and appears to play a substantial role in the rotation of the Neogene formations.

From a hydrogeological aspect, groundwater occurs in the alluvial sediments of the deltaic plain of Pineios River, which based on [25], is not identified throughout the entire deltaic basin, but only at its central and northern parts. Below the alluvial sediments, a clay formation occurs, as revealed from wells logs, along with a deeper confined aquifer consisting mainly by conglomerates. Therefore, two major aquifer systems are defined: the phreatic and the confined deep aquifer.

## Methodology

Our investigation along the deltaic plain of Pineios River is comprised of two parts, the subsurface investigation with geophysical methods and the surficial one, with the contribution of satellite image processing. The coordinate system used in all data is the Greek Geodetic Reference System 1987 (GGRS87/Greek Grid).



**Fig. 1.** Geological map of the study area, modified by [33], along with the location of the Transient Electromagnetic soundings and boreholes [35].

*Geophysical survey for subsurface investigation*

A geophysical survey has been conducted along the deltaic area of Pineios River for the delineation of the subsurface regime and hydrogeological characteristics. In this paper, we will deal with the results of the Transient Electromagnetic Method (TEM) that has been carried out in the area along with other geophysical methods in previous studies, such as Vertical Electrical Soundings (VES) and gravity measurements. The main objective of this geophysical survey was to calculate the thickness of the deltaic deposits followed by the deposition of the transgressive sediments.

The Transient Electromagnetic Method (TEM) has been used for hydrogeological applications [36–38] and for the determination of the subsurface geological structure as well [39–41]. Over the last decades the TEM method has become increasingly popular for environmental and groundwater investigation [42–43]. TEM is a method highly sensitive to low-resistivity layers, successfully applied in the past by other researchers, especially for mapping coastal aquifers and seawater intrusion [44–45].



Fig. 2. The set-up of in-loop field configuration (left) and a sounding location during data acquisition.

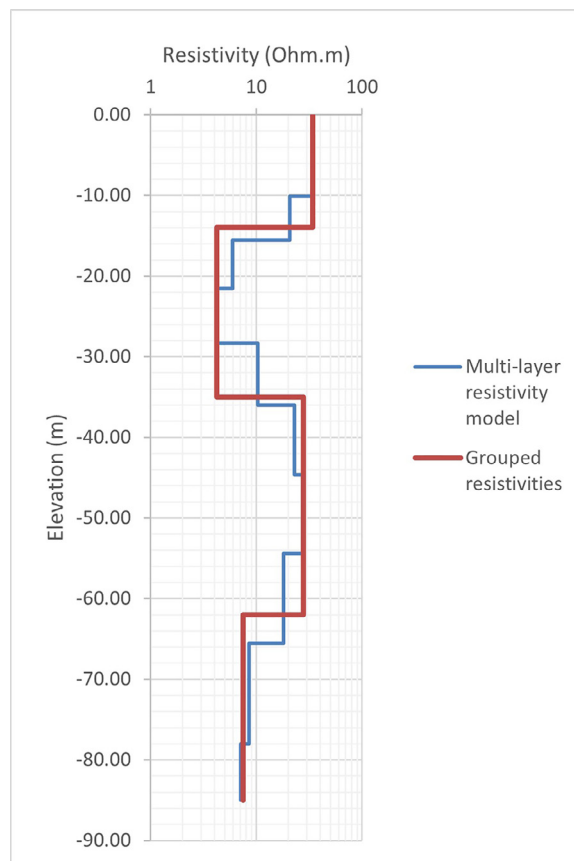
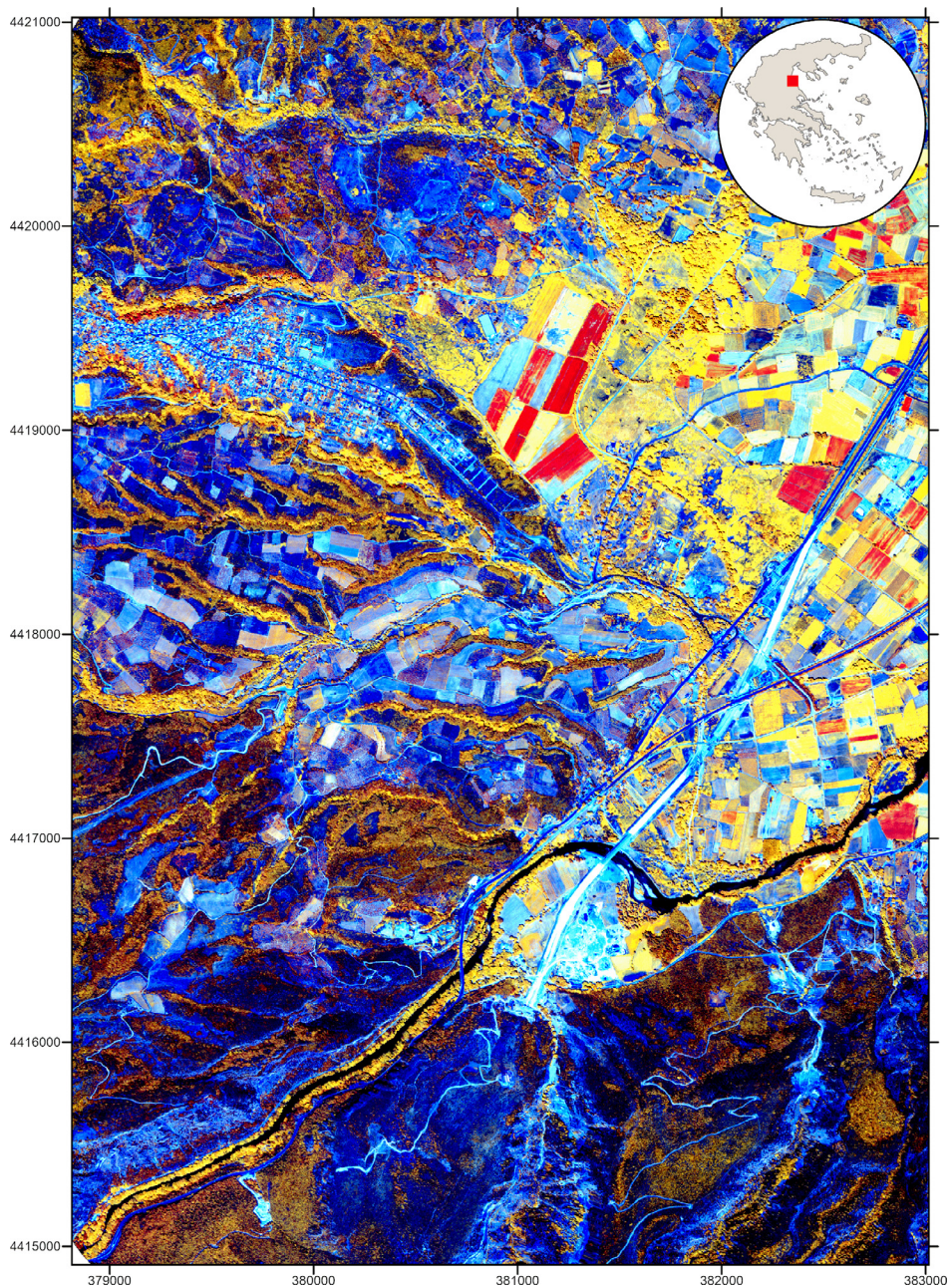


Fig. 3. The resistivities calculated for the same TEM sounding as a multi-layer model (blue color) and as a four-layer model (red color).

A total of 127 TEM soundings (Fig.1) were acquired across the entire deltaic valley. The TEM measurements were acquired with ABEM’s WalkTEM instrument. The field configuration for data acquisition was comprised of a 40 m x 40 m square transmitter loop with two in-loop antennas, the RC-200 (10 m x 10 m) and the RC-5 (0.5 m x 0.5 m) each with different receiver areas. In Fig. 2 the described configuration array deployed in the field is presented.

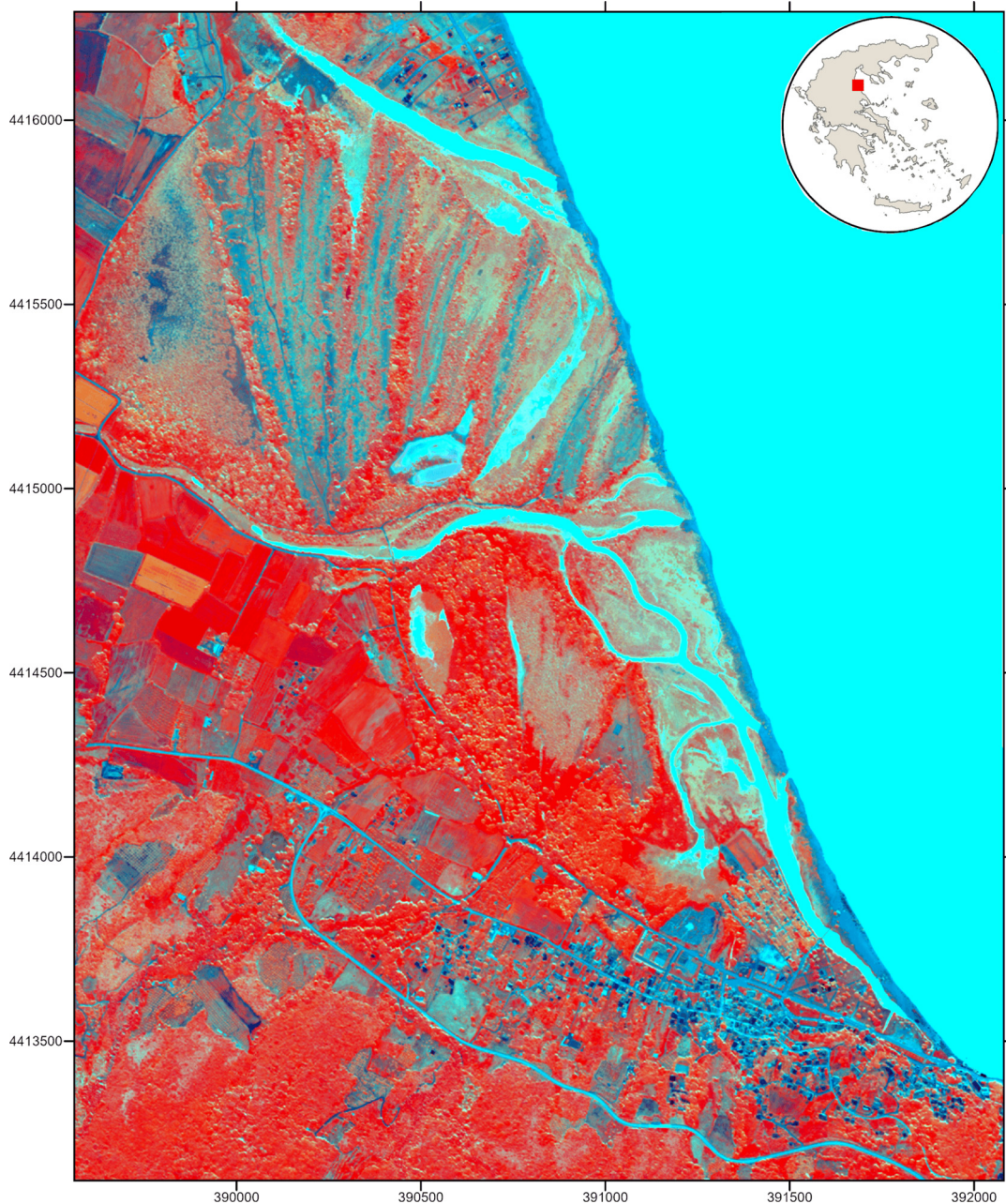
The processing of the TEM soundings and their inversion were carried out with ViewTEM software leading to their corresponding multilayer resistivity models. Each multi-layer resistivity model was transformed into a few-layer resistivity model. An example of this procedure is presented in Fig. 3, where the ‘Resistivity– Elevation’ chart is illustrated, presenting the same TEM sounding in both ways; as a multi-layer resistivity model and as a four-layer geophysical model. The layers’ boundaries and resistivity values are given in Table 1.



**Fig. 4.** False color composite by the combination of spectral bands 8, 7, 6. This combination highlights the drainage network due to the riparian vegetation (yellow) while built-up areas and bare soils appear blue.

**Table 1**  
Geophysical layers extracted from the four-layer resistivity model of the above TEM sounding.

Geophysical layer	Z-Top (m)	Z-Base (m)	$\rho$ (Ohm.m)	Lithology
1	2.0	-14.0	34.0	Alluvial deposits
2	-14.0	-35.0	4.2	Clay formation
3	-35.0	-62.0	28.0	Transgressive deposits
4	-62.0		7.5	Blue Schists



**Fig. 5.** False color composite by the combination of spectral indices MSAVI2, WV-BI, and WV-WI. The beach is clearly distinguished from other bare soils. The beach ridges and sand dunes appear very detailed.

The geological interpretation of the geophysical data was achieved calibrated with available drilling data (Fig. 1) from [27]. Beyond that, the interpretation of the TEM soundings, was also cross-checked based on the published results of the geoelectrical method carried out by the authors [23–26] but also with the recently published results by [28] regarding the investigation of the deeper geological and tectonic structure of the deltaic plain by gravity measurements.

The surface lithology in the deltaic plain that is structured by alluvial deposits or sand dunes (at the coastal area) (Fig. 1) have been investigated with resistivity values ranging between 17 and 45 Ohm.m and 66–120 Ohm.m respectively. The underlying lithological layer, observed throughout the study area, corresponds to an impermeable clay formation, with resistivity of 1–7 Ohm.m. These two lithological units comprise the deltaic deposits. The third lithological unit, investigated by almost all TEM soundings (114/127 soundings), is consisted mainly of sands and gravels with small amount of clay and represents the transgressive deposits of the last interglacial period and is characterized by resistivity values of 10–30 Ohm.m. In many TEM soundings, an additional layer was also

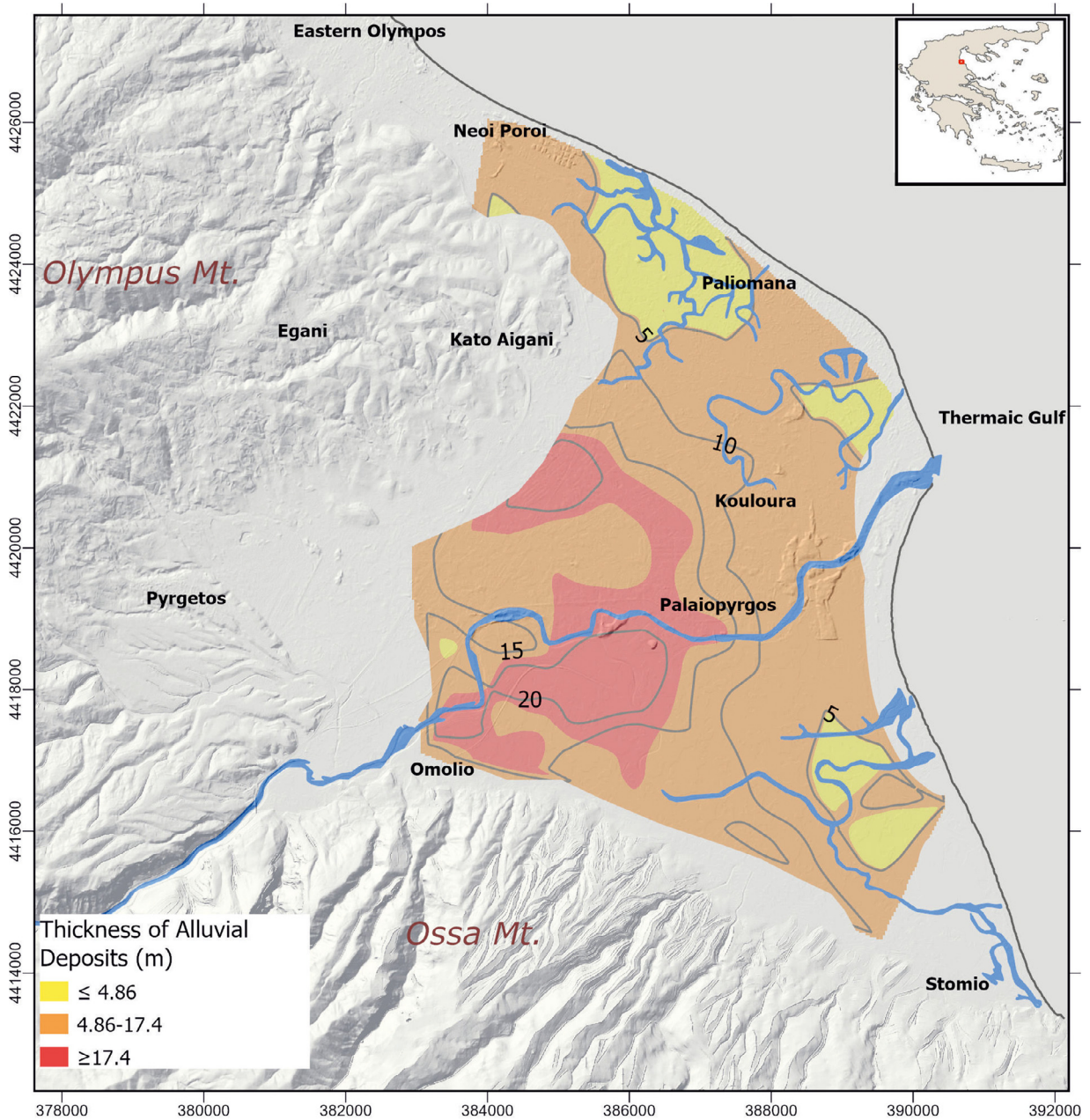


Fig. 6. Map presenting the distribution of the thickness of the alluvial deposits in the investigation area. The classes' limits were calculated based on the standard deviation and mean values of the formation.

investigated, corresponding either to the Neogene formations that appear west and northwest of the deltaic plain, or the roof of the alpine basement (Blue schists or Crystalline Limestones).

*Satellite image processing for surficial investigation*

A very high resolution WorldView-2 image acquired on 27/07/2013 has been processed. The 8-band multispectral imagery was at 2 m resolution and the panchromatic imagery was at 50 cm resolution. The high spatial resolution enables the discrimination of fine details and the high spectral resolution provides detailed information on such diverse areas. The processing of WorldView-2 satellite images was performed with the ERDAS Imagine 2014 software, as well as the calculation of ten spectral indices (Table 2).

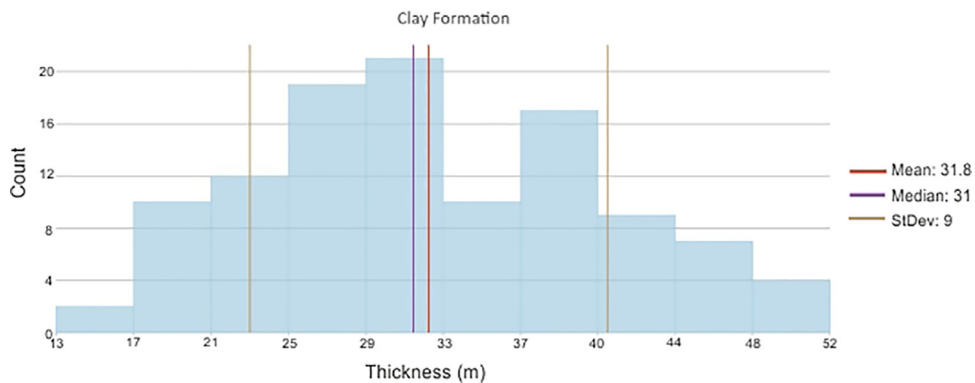
The objective of the surface investigation was to identify the appropriate combination of spectral bands / spectral indices to highlight various biotic / abiotic characteristics of the delta. As a result, six false color composites of the area were produced combining

**Table 2**  
The Spectral Indices calculated for the study area.

Spectral Index	Formula	Reference
Normalized Difference Vegetation Index	$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$	[46]
Iron Oxide	$IRON\ OXIDE = \frac{RED}{BLUE}$	[47]
Improved Modified Chlorophyll Absorption Rate Index	$MCARI2 = \frac{1.5[2.5(\rho_{800} - \rho_{670}) - 1.3(\rho_{800} - \rho_{550})]}{\sqrt{(2*\rho_{800} + 1)^2 - (6*\rho_{800} - 5*\sqrt{\rho_{670}}) - 0.5}}$	[48]
Modified Soil Adjusted Vegetation Index 2	$MSAVI2 = \frac{2 * NIR + 1 - \sqrt{(2 * NIR + 1)^2 - 8(NIR - Red)}}{2}$	[49]
Modified Red Edge Simple Ratio Index	$MRESR = \frac{\rho_{750} - \rho_{445}}{\rho_{705} - \rho_{445}}$	[50]
WorldView Soil Index	$WV - SI = \frac{(Green - Yellow)}{(Green + Yellow)}$	[51]
WorldView Water Index	$WV - WI = \frac{(Coastal - NIR2)}{(Coastal + NIR2)}$	
WorldView New Iron Index	$WV - II = \frac{(Green * Yellow)}{(Blue * 1000)}$	
WorldView Built-Up Index	$WV - BI = \frac{(Coastal - Red Edge)}{(Coastal + Red Edge)}$	

**Table 3**  
The benefits of the six false color composites of the area that were produced combining spectral bands.

Spectral band combination	Benefits
(7, 6, 5)	<ul style="list-style-type: none"> <li>✓ conifers appear in brown-green shades</li> <li>✓ grass and crops tend to appear in yellow and orange shades</li> <li>✓ bare soils and rock outcrops show up in grayish shades</li> </ul>
(8, 4, 1)	<ul style="list-style-type: none"> <li>✓ quick recognition of land use and land cover patterns</li> <li>✓ vegetation shows up in red, built-up areas appear blue with highly variable colors representing vegetation changes and structures</li> </ul>
(3, 2, 1)	<ul style="list-style-type: none"> <li>✓ water penetration and bathymetric information</li> </ul>
(4, 8, 7)	<ul style="list-style-type: none"> <li>✓ highlights the presence of sediment in the water</li> </ul>
(8, 7, 6)	<ul style="list-style-type: none"> <li>✓ vegetation in light colored yellows</li> <li>✓ high degree of contrast between vegetation, water, and built-up features</li> </ul>
(7, 3, 2)	<ul style="list-style-type: none"> <li>✓ illustrate built-up features and roads</li> <li>✓ high degree of contrast between shoreline and seawater</li> </ul>



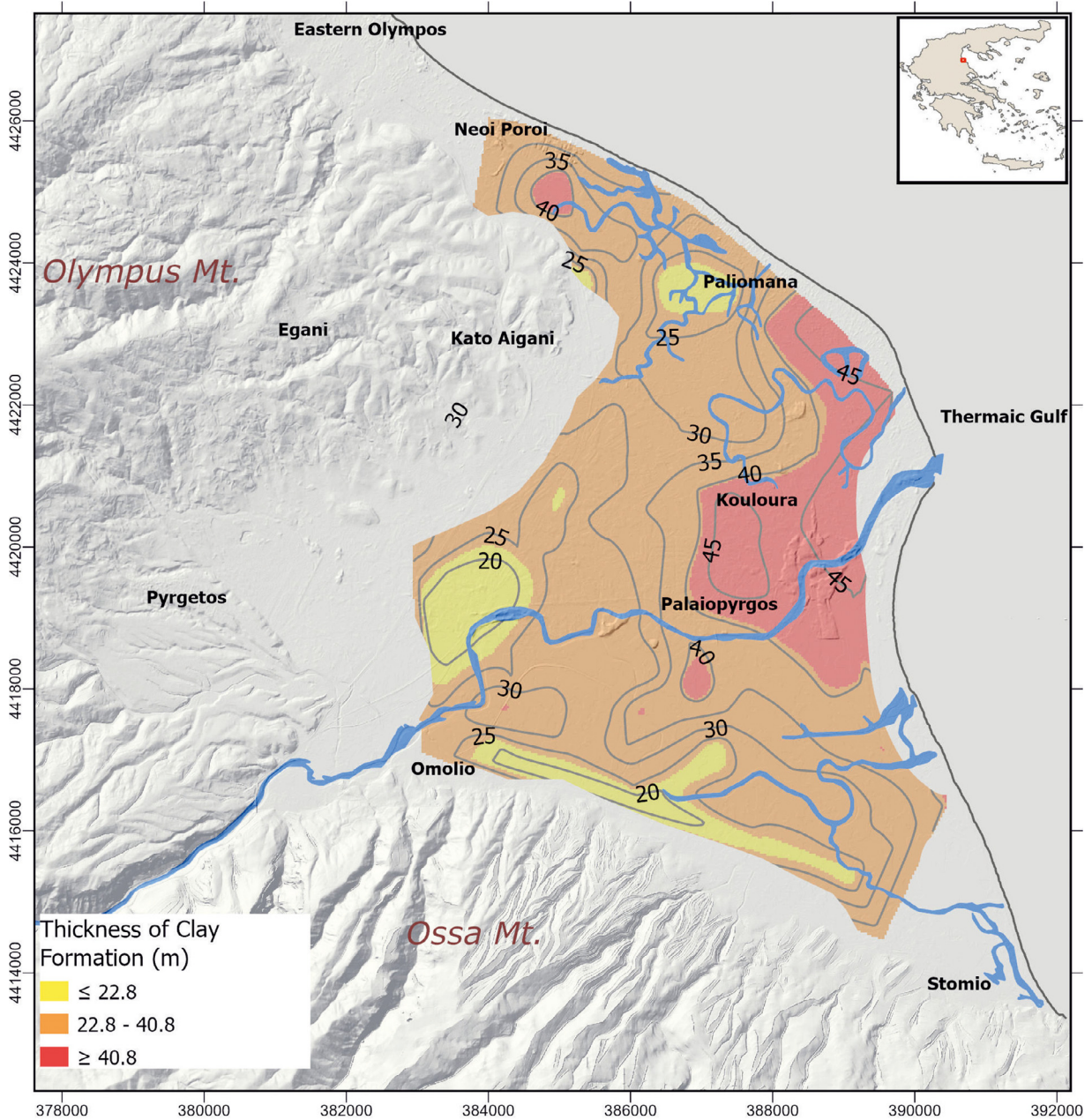
**Fig. 7.** The results of the statistical analysis performed for the Clay Formation.

spectral bands and additional five false color composites by combining several spectral indices. The spectral band and spectral indices combinations used in this study along with their benefits are given in Tables 3 and 4 respectively.

In Fig. 4 we can clearly distinguish the different land uses in this area of the delta where Pineios River exits Tempi valley. The combination used is spectral bands 8, 7, 6. The roads, railway, settlements, bare soils and rocky areas appear in blue and grayish shades, while yellow, orange and red colors represent different types of vegetation and crops. Particularly, we can note the contrast presented between the riparian vegetation and the surrounding area, an element that delineates the hydrographic network. The river appears dark blue and black.

**Table 4**  
The benefits of the five false color composites of the area that were produced combining spectral indices.

Spectral indices combination	Benefits
(MSAVI2, WV-BI, WV-WI)	shoreline clearly distinguished from other bare soils and sand dunes
(MSR705, R31, WV-II)	highlights the drainage network due to the riparian vegetation
(WV-SI, IRON INDEX, MSR705)	water penetration
(WV-II, WV-BI, WV-WI)	high degree of contrast between crops and bare soils, rock outcrops and sands
(WV-VI, NDVI, MACARI2)	highlights water bodies and soil moisture



**Fig. 8.** Map presenting the distribution of the thickness of the clay formations in the investigation area. The classes' limits were calculated based on the standard deviation and mean values of the formation.

The combination of spectral indices MSAVI2, WV-BI, and WV-WI is shown in Fig. 5. This is a very detailed imagery of the deltaic plain north of Stomio settlement. Vegetation appears in red color while built-up areas and roads in blue. The beach along with the sand dunes and the beach ridges with orientation NE-SW, are very well defined.

**Results and discussion**

Our main interest of the applied methodology and this paper is the deltaic deposits. Taking into consideration the elevation of each TEM station and its model, the absolute heights of the top and the base of the alluvial deposits were calculated individually, as well as the point thickness of the deposits. The same procedure was also followed for the clay formation.

The map in Fig. 6 shows the spatial distribution of the thickness for the alluvial deposits along the delta plain. The formation has an average thickness of 11.1 m, the mean value was calculated 9.5 and the standard deviation equal to 6.28. The minimum value is 1.3 m and the maximum value is 28 m. Based on the standard deviation and the mean value calculated for the alluvial deposits, we

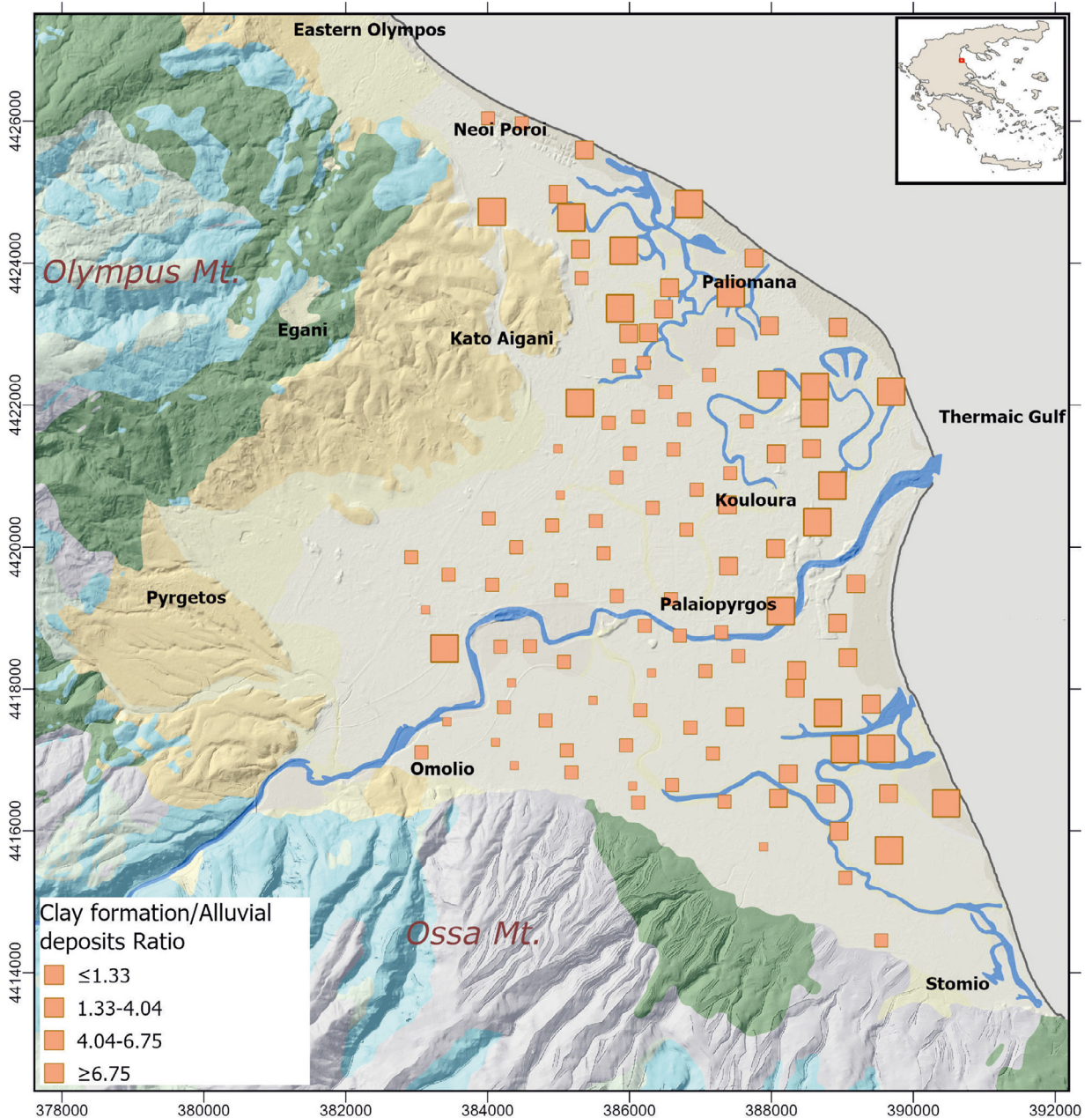


Fig. 9. Distribution of the values of the ratio ‘Thickness of Clay Formation / Thickness of Alluvial Deposits’.

categorized their spatial distribution along the deltaic area in three zones/classes (yellow, orange and red). These 3 classes are the following: i)  $\leq 4.86$  m ii)  $4.86 - 17.4$  m iii)  $\geq 17.4$  m. The first (yellow areas) and third (red area) classes include values of thickness beyond a standard deviation from the mean value. The highest values of thickness (greater than 15 m) of the alluvial deposits are located in the areas west of Kouloura settlement and southwest of Palaiopyrgos settlement (red zone). Respectively, the smallest values of thickness (less than 5 m) can be observed north and southeast (yellow zone). The alluvial deposits covering the rest of the deltaic area have been identified with thickness ranging between 4.86 and 17.4 m (orange zone).

In addition, a statistical analysis of these data was performed for the calculation of important characteristics, but also a short and clear presentation that will enhance the spatial presentation of the results. The Natural Neighbor spatial interpolation method was used to construct the raster data.

The Histogram Graph of Fig. 7 refers to the values calculated for the thickness of the Clay Formation throughout the study area. We observe that the formation has an average thickness of 31.8 m, the median was calculated 31 and the standard deviation equal to 9. The minimum value is 13 m and the maximum 52 m. Regarding the spatial distribution of the thickness of Clay Formation in the deltaic plain (Fig. 8), the highest values are observed throughout the central and eastern part of Pineios River deltaic plain. The formation exceeds 45 m of thickness in the area south and east of Kouloura settlement.

Based on the values of the standard deviation and the mean value for Clay Formation, TEM soundings were again classified in the following 3 classes of thickness: i)  $\leq 22.8$  m, ii)  $22.8 - 40.8$  m iii)  $\geq 40.8$  m. The map in Fig. 8 shows the result of this classification spatially distributed along the deltaic plain. The first (yellow areas) and third class (red areas) include values beyond a standard deviation from the mean value. Small values are limited mainly in the southern part of the deltaic plain, parallel to the slopes of Ossa Mt. but also in the western part of the deltaic plain, in the area north of Omolio settlement. A small appearance of values of the first class is found in the north, in Paliomana settlement. Values of the third class occupy the area of the present estuary and inland the settlement of Kouloura.

The ratio 'Thickness of Clay Formation / Thickness of Alluvium Deposits' was also calculated in order to compare the distribution of thickness of the two formations appearing in the study area. The minimum value of the ratio is 0.74 and the maximum 14.2. The average value of the ratio is 4.04, the median 3.12 and the standard deviation 2.71. The map in Fig. 9 presents the spatial distribution of the 'Thickness of Clay Formation / Thickness of Alluvial Deposits' ratio along the deltaic plain. We observe that the ratio gets its maximum values in the areas of the present and past estuary (north of Stomio settlement) as well as further north in the area of Paliomana settlement. We can also notice one sounding location with high ratio value north of Omolio settlement.

## Conclusions

In general, the applied methodology provided valuable data for the subsurface structure of a deltaic plain along with important information regarding its surficial characteristics. The statistical analysis of the geophysical interpretation can provide even better understanding of the river delta structure and can contribute to the understanding of the physical-geographical characteristics of a river delta area.

Regarding the results and the interpretation of the geophysical survey, new information regarding the subsurface structure has been obtained. The average thickness of the Alluvial deposits' formation has been estimated to 11 m and is hosting the shallow unconfined aquifer. These deposits were formed during the growth of Pineios River Delta that began 4–5,000 years BP. Regarding the Clay formation, which is an impermeable formation, its average thickness has been calculated equal to 32 m. Basically, it represents the pro-deltaic fine-grained deposits of the growing delta during the Upper Holocene. Finally, the transgressive deposits which are consisted mainly of sands and gravels with small amount of clay, host an aquifer, artesian in places, and overlays the Neogene formations which can be considered as the paleosurface during the last glacial period (sea level was 120–130 m below present sea level).

The statistical analysis of the thickness of the lithological units of the deltaic area and their ratio thickness, also revealed some important results. More specifically, the greater values of thickness of the Alluvial deposits are limited to the central part of the deltaic plain and can be associated with the frequent flooding phenomena that are being observed in this area. On the other hand, the smallest thickness of this formation is located i) in the area north in the deltaic plain, where many meanders and isolated parts of old riverbeds are present, ii) in the area of the present estuary and iii) in the old estuary area, north of the Stomio settlement. Regarding the clay formation, small thickness values mainly appear i) in the southern part of the deltaic plain near Ossa Mt.'s slopes, ii) in the western part in the deltaic plain north of the settlement of Omolio and iii) in the north in Paliomana settlement. On the other hand, the high values of clay thickness appear i) in the eastern part of the Pineios Delta, ii) at the present estuary area and iii) inland, around Kouloura settlement. This seems to be consistent with the interpretation of the marine acoustic survey conducted in the area [52], which has estimated the thickness of the deltaic deposits in the central part of the Pineios Delta up to 35 m.

The Clay Formation Thickness/Alluvial deposits Thickness ratio gets its maximum values in the areas where the fluvial processes dominate through the mainstream or the past tributaries. These locations are: i) the area of the present estuary, ii) the old estuaries (Stomio settlement) and iii) further north in the area with the appearance of the large number of meanders. Finally, one TEM sounding, remote from the areas just indicated, that appears with high ratio value (north of Omolio settlement) coincides with the location where Pineios River changes abruptly two times its direction of flow.

Regarding the surface investigation of the area, we came up with some conclusions, based on the results of the combinations of the spectral bands and indices that we applied. More specifically, we observed that the combination of spectral bands 8, 7, 6 can be used to clearly distinguish the land uses with the high degree of contrast between vegetation, water, and built-up features. The vegetation

is colored yellow and orange while the bare soils, rocky areas and built-up features appear blue and gray, something that greatly outlines the hydrographic network of the area as a result of the intense difference of the riparian vegetation. This can be very useful in monitoring the whole basin area and detecting possible changes in the inflow, like stream piracy that can change the routing of water and sediment and may have an effect on landscape evolution. Moreover, the combination of spectral indices MSAVI2, WV-BI, WV-WI can be very helpful to geomorphological mapping of the deltaic plain, given the fact that many features such as the beach ridges, sand dunes and the part of the sandy beach appear very detailed with this combination of spectral indices.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### CRediT authorship contribution statement

**Georgia S. Mitsika:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **John D. Alexopoulos:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Emmanuel Vassilakis:** Conceptualization, Methodology, Resources, Data curation, Writing – review & editing, Supervision. **Spyridon Dilalos:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Serafim E. Poulos:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

### Data Availability

Data will be made available on request.

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### References

- [1] K.C. Seto, Exploring the dynamics of migration to mega-delta cities in Asia and Africa: contemporary drivers and future scenarios, *Glob. Environ. Chang.* 21 (2011) S94–S107, doi:[10.1016/j.gloenvcha.2011.08.0.](#)
- [2] J.P. Syvitski, A.J. Kettner, I. Overeem, E.W. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, R.J. Nicholls, Sinking deltas due to human activities, *Nat. Geosci.* 2 (10) (2009) 681–686, doi:[10.1038/ngeo629.](#)
- [3] C. Kuenzer, F.G. Renaud, Climate and environmental change in river deltas globally: expected impacts, resilience, and adaptation, in: F.G. Renaud, C. Kuenzer (Eds.), *The Mekong Delta System: Interdisciplinary Analyses of a River Delta*, Springer, The Netherlands, Dordrecht, 2012, pp. 7–46, doi:[10.1007/978-94-007-3962-8\\_2.](#)
- [4] R. Schmitt, Z. Rubin, G. Kondolf, Losing ground-scenarios of land loss as consequence of shifting sediment budgets in the Mekong Delta, *Geomorphology* 294 (2017) 58–69, doi:[10.1016/j.geomorph.2017.04.029.](#)
- [5] K. Gaki-Papanastassiou, A.B. Cundy, H. Maroukian, Fluvial versus tectonic controls on the late Holocene geomorphic and sedimentary evolution of a small Mediterranean fan delta system, *J. Geol.* 119 (2) (2011) 221–234, doi:[10.1086/658144.](#)
- [6] A. Karnieli, N. Agam, R.T. Pinker, M. Anderson, M.L. Imhoff, G.G. Gutman, N. Panov, A. Goldberg, Use of NDVI and Land Surface Temperature for Drought Assessment: merits and Limitations, *Climate* 23 (2010) 618–633, doi:[10.1175/2009JCLI2900.1.](#)
- [7] G. Marchisio, F. Pacifici, C. Padwick, On the relative predictive value of the new spectral bands in the WorldView-2 sensor, in: *2010 IEEE International Geoscience and Remote Sensing Symposium, 2010*, pp. 2723–2726.
- [8] A. Filintas, P. Dioudis, C. Prochaska, GIS modeling of the impact of drip irrigation, of water quality and of soil’s available water capacity on Zea mays L. biomass yield and its biofuel potential, *Desalination Water Treat* 13 (1–3) (2010) 303–319, doi:[10.5004/dwt.2010.1038.](#)
- [9] G. Stamatis, K. Parpodis, A. Filintas, E. Zagana, Groundwater quality, nitrate pollution and irrigation environmental management in the Neogene sediments of an agricultural region in central Thessaly (Greece), *Environ Earth Sci* 64 (4) (2011) 1081–1105, doi:[10.1007/s12665-011-0926-y.](#)
- [10] R.L. Caldwell, D.A. Edmonds, S. Baumgardner, C. Paola, S. Roy, J.H. Nienhuis, A global delta dataset and the environmental variables that predict delta formation, *Earth Surface Dynamics* 7 (3) (2019) 773–787, doi:[10.5194/esurf-7-773-2019.](#)
- [11] J.H. Nienhuis, A.D. Ashton, L. Giosan, What makes a delta wave-dominated? *Geology* 43 (6) (2015) 511–514, doi:[10.1130/G36518.1.](#)
- [12] J.H. Nienhuis, A.J.F. Hoitink, T.E. Törnqvist, Future change to tide-influenced deltas, *Geophys. Res. Lett.* 45 (8) (2018) 3499–3507, doi:[10.1029/2018GL077638.](#)
- [13] J.P. Syvitski, C.J. Vörösmarty, A.J. Kettner, P. Green, Impact of humans on the flux of terrestrial sediment to the global coastal ocean, *Science* 308 (5720) (2005) 376–380, doi:[10.1126/science.1109454.](#)
- [14] J.P. Syvitski, Y. Saito, Morphodynamics of deltas under the influence of humans, *Glob Planet Change* 57 (3) (2007) 261–282, doi:[10.1016/j.gloplacha.2006.12.001.](#)
- [15] J. Martínez, J. Benavente, J.L. García-Aróstegui, M.C. Hidalgo, J. Rey, Contribution of electrical resistivity tomography to the study of detrital aquifers affected by seawater intrusion–extrusion effects: the river Vélez delta (Vélez-Málaga, southern Spain), *Eng. Geol.* 108 (2009) 161–168, doi:[10.1016/j.enggeo.2009.07.004.](#)
- [16] A. Koutsios, N. Kontopoulos, D. Kalisperi, P. Soupios, P. Avramidis, Sedimentological and geophysical observations in the delta plain of Selinous river, Sncient Helike, Northern Peloponnesus Greece, *Bulletin of the Geological Society of Greece* 43 (2) (2010) 654–662 Patras, doi:[10.12681/bgsg.11228.](#)
- [17] I. Kioungkis, T. Tzeveleki, F. Pliakas, I. Diamantis, A. Pechtelidis, Geophysical research of groundwater degradation at the eastern Nestos River Delta, NE Greece, *Advances in the Research of Aquatic Environment* 1 (2011), doi:[10.1007/978-3-642-19902-8.](#)

- [18] L.T. Tran, F. Larsen, N.Q. Pham, A.V. Christiansen, N. Tran, H.V. Vu, L.V. Tran, H.V. Hoang, K. Hinsby, Origin and extent of fresh groundwater, salty paleowaters and recent saltwater intrusions in Red River flood plain aquifers, Vietnam, *Hydrogeol J* 20 (2012) 1295–1313, doi:10.1007/s10040-012-0874-y.
- [19] A. Khalil, K. Mansour, T. Rabeh, A. Basheer, M.A. Zaher, K. Ali, Geophysical Evaluation for Evidence of Recharging the Pleistocene Aquifer at El-Nubariya Area, West Nile Delta, Egypt, *International Journal of Geosciences* 5 (2014) 324–340, doi:10.4236/ijg.2014.53032.
- [20] Alexopoulos, J.D., Dilalos, S., Poulos, S., Ghionis, G., Mavroulis, S. (2014). Application of geoelectrical techniques in the investigation of a coastal sand dune field. In: *20th European Meeting of Environmental and Engineering Geophysics*. Tu\_PA2\_01. Athens, Greece; 5p. <https://doi.org/10.3997/2214-4609.20142025>
- [21] H. Shaaban, G. El-Qady, E. Al-Sayed, H. Ghazala, A.I. Taha, Shallow groundwater investigation using time-domain electromagnetic (TEM) method at Itay El-Baroud, Nile Delta, Egypt, *NRIAG Journal of Astronomy and Geophysics* 5 (2) (2016) 323–333, doi:10.1016/j.nrjag.2016.05.004.
- [22] I.M. Ibraheem, G.M. El-Qady, A. ElGalladi, Hydrogeophysical and structural investigation using VES and TDEM data: a case study at El-Nubariya–Wadi El-Natrun area, west Nile Delta, Egypt, *NRIAG Journal of Astronomy and Geophysics* 5 (1) (2016) 198–215, doi:10.1016/j.nrjag.2016.04.004.
- [23] J. Alexopoulos, The contribution of the geo-electrical parameters distribution in the investigation of the paleo geographical evolution of the deltaic plain of Pineios river (Thessaly), in: *Proceeding of 10thCongress of the Hellenic Geographical Society, Thessaloniki, Greece, 2014*, pp. 1717–1723.
- [24] J. Alexopoulos, S. Dilalos, E. Vassilakis, D. Michelioudakis, S. Mavroulis, S. Poulos, Preliminary evaluation of geophysical and geological data in Pineios River Delta plain (Thessaly), in: *Proceeding of 10thCongress of the Hellenic Geographical Society, Thessaloniki, Greece, 2014*, pp. 1724–1731.
- [25] J.D. Alexopoulos, I. Matiatos, S. Dilalos, V. E. A. Panagopoulos, G. Ghionis, S Poulos, Investigation of the phreatic aquifer development at the Pineios Delta basin (Thessaly), through a combination of geophysical and hydrogeological data, in: *Proceeding of 10thCongress of the Hellenic Geographical Society, Thessaloniki, Greece, 2014*, pp. 1130–1139.
- [26] J.D. Alexopoulos, S. Dilalos, G.S. Mitsika, S.E. Poulos, Mapping of deltaic aquifers with the combined application of DC and TEM soundings, in: *Near Surface Geoscience 2019-25thEuropean Meeting of Environmental and Engineering Geophysics*, 2019, p. 5, doi:10.3997/2214-4609.201902468. We\_25\_P13.
- [27] S. Dilalos, J.D. Alexopoulos, Vassilakis Em, S.E Poulos, Investigation of the structural control of a deltaic valley with geophysical methods. The case study of Pineios river delta (Thessaly, Greece), *J Appl Geophy* 202 (2022) 104652, doi:10.1016/j.jappgeo.2022.104652.
- [28] Poulos, S., Alexopoulos, J., Dassenakis, M., Kotsopoulos, S., Lazogiannis, K., Matiatos, J., Paraskevopoulou, V., Sifnioti, D., Ghionis G., Alexiou, I. (2013). An investigation of the impact of the climate change on river deltas: case study: the delta of r. Pineios (Thessaly, Greece) - concept and preliminary results on surface water environmental state. In: *13th International Conference on Environmental Science and Technology*. CEST2013\_0372, 8p.,Athens
- [29] I. Matiatos, V. Paraskevopoulou, K. Lazogiannis, F. Botsou, M. Dassenakis, G. Ghionis, Alexopoulos JD, S.E. Poulos, Surface–ground water interactions and hydro-geochemical evolution in a fluvio-deltaic setting: the case study of the Pineios River delta, *J Hydrol (Amst)* (2018) 236–249, doi:10.1016/j.jhydrol.2018.03.067.
- [30] K. Lazogiannis, S. Poulos, D.H. Giannouli, D.E. Sifnioti, K. Tsanakas, A. Tsoutsia, S. Dilalos, G. Gkionis, S. Petrakis, Study of morfodynamic processes of Pinios Delta coastline (Thessaly), *Proceeding of 10thCongress of the Hellenic Geographical Society, 1744-1755, 22-24 October 2014, 2014*.
- [31] K. Lazogiannis, S. Poulos, D.H. Giannouli, D.E. Sifnioti, K. Tsanakas, A. Tsoutsia, S. Dilalos, G. Gkionis, Em. Vassilakis, S. Petrakis, D. Tarasi, G. Terezakis, Morphological changes along deltaic coastline of pinios river (Thessaly), *Geographies*, 26 (2015) 51–58.
- [32] E. Karymbalis, K. Gaki-Papanastassiou, K. Tsanakas, M. Ferentinou, Geomorphology of the Pineios River delta, Central Greece, *J Maps* 12 (1) (2016) 12–21, doi:10.1080/17445647.2016.1153356.
- [33] G. Katsikatsos, G. Migros, Rapsani Sheet – Geological Map in Scale 1:50000, IGME, Athens, Greece, 1982.
- [34] E. Vassilakis, S. Mavroulis, J.D. Alexopoulos, S Dilalos, Morphotectonic evolution of the Pineios Deltaic area (Thessaly), in: *Proceedings of 10thCongress of the Hellenic Geographical Society, Thessaloniki, Greece, 2014*, pp. 1671–1684.
- [35] A. Manakos, V. Tsioumas, Institute of Geology and Mineral Research, Department of water resources and environment, Hydrogeology, Prefecture of Central Macedonia, *Hydrogeological Study of Thessaly Water District (GR 08)*, 2010.
- [36] J.E. Danielsen, E. Auken, F. Jorgensen, V.H. Sondergaard, K.I. Sorensen, The Application of the Transient Electromagnetic Method in Hydrogeophysical Surveys, *J Appl Geophy* 53 (2003) 181–198, doi:10.1016/j.jappgeo.2003.08.004.
- [37] M. Corriols, M. Rym Nielsen, T. Dahlin, N.B. Christensen, Aquifer investigations in the León-Chinandega plains, Nicaragua, using electromagnetic and electrical methods, *Near Surface Geophysics* 7 (5–6) (2009) 413–426, doi:10.3997/1873-0604.2009034.
- [38] H. El-Kaliouby, O. Abdalla, Application of time-domain electromagnetic method in mapping saltwater intrusion of a coastal alluvial aquifer, North Oman, *J Appl Geophy* 115 (2015) 59–64, doi:10.1016/j.jappgeo.2015.02.003.
- [39] J.D. Alexopoulos, S. Dilalos, G.S. Mitsika, Preliminary results of the application of Transient Electromagnetic Method in the area of Karla Lake (East Thessaly basin, Greece), in: *Proceedings of 11thInternational Hydrogeological Congress, 2, Athens, Greece, 2017*, pp. 103–112.
- [40] J.D. Alexopoulos, S. Dilalos, G.S. Mitsika, Em. Vassilakis, S.E. Poulos, A geophysical approach to the phenomenon of ground fissures at the East Thessaly basin (Greece), in: *Near Surface Geoscience 2019-25thEuropean Meeting of Environmental and Engineering Geophysics*, 2019, p. 5, doi:10.3997/2214-4609.201902379. Mo\_25\_P14.
- [41] P.O. Barsukov, E.B. Fainberg, Mapping bedrock topography and moraine deposits by transient electromagnetic sounding: oslo graben, Norway, *Near Surface Geophysics* 18 (2) (2020) 123–133, doi:10.1002/nsg.12070.
- [42] E. Auken, F. Jorgensen, K.I. Sorensen, Large-Scale TEM Investigation for Ground-Water, *Explor. Geophys.* 33 (2003) 188–194, doi:10.1071/EG03188.
- [43] D. Kalisperi, P. Soupios, M. Kouli, P. Barsukov, S. Kershaw, P. Collins, P. Vallianatos, Coastal Aquifer Assessment using Geophysical Methods (TEM, VES), Case Study: northern Crete, Greece, in: *3rd IASME /WSEAS (GES'09)*, Cambridge, UK, 2009, pp. 158–164.
- [44] C.H. Yang, L.T. Tong, C.F. Huang, Combined application of dc and TEM to sea-water intrusion mapping, *Geophysics* 64 (2) (1999) 417–425, doi:10.1190/1.1444546.
- [45] Y. Albouy, P. Andrieux, G. Rakotondraso, M. Rit, M. Desclotres, J.L. Join, E. Rasolomanana, Mapping Coastal Aquifers by Joint Inversion of DC and TEM Soundings-Three Case Histories, *Groundwater* 39 (1) (2001) 87–97, doi:10.1111/j.1745-6584.2001.tb00354.x.
- [46] J. Rouse, R. Haas, J. Schell, D. Deering, Monitoring Vegetation Systems in the Great Plains with ERTS, in: *3rd ERTS Symposium, NASA, 1973*, pp. 309–317.
- [47] D. Segal, Theoretical Basis for Differentiation of Ferric-Iron Bearing Minerals, Using Landsat MSS Data, in: *Proceedings of Symposium for Remote Sensing of Environment2ndThematic Conference on Remote Sensing for Exploratory Geology*, Fort Worth, 1982, pp. 949–951.
- [48] D. Haboudane, J.R. Miller, E. Pattey, P.J. Zarco-Tejada, I.B. Strachan, Hyperspectral Vegetation Indices and Novel Algorithms for Predicting Green LAI of Crop Canopies: modeling and Validation in the Context of Precision Agriculture, *Remote Sens. Environ.* 90 (2004) 337–352, doi:10.1016/j.rse.2003.12.013.
- [49] J. Qi, A. Chehbouni, A. Huete, Y. Kerr, S. Soroshian, A Modified Soil Adjusted Vegetation Index, *Remote Sens. Environ.* 48 (1973) 119–126, doi:10.1016/0034-4257(94)90134-1.
- [50] B. Datt, A New Reflectance Index for Remote Sensing of Chlorophyll Content in Higher Plants: tests Using Eucalyptus Leaves, *J. Plant Physiol.* 154 (1999) 30–36, doi:10.1016/S0176-1617(99)80314-9.
- [51] Wolf, A. (2010). Using WorldView 2 Vis-NIR MSI Imagery to Support Land Mapping and Feature Extraction Using Normalized Difference Index Ratios. Unpublished report, Longmont, CO: DigitalGlobe.
- [52] I. Gazis, K. Lazogiannis, T. Hasiotis, A.F. Velegrakis, S.E. Poulos, Modern Sediment Processes at the submarine area of the Delta of Pineios River (Thessaly), in: *Proceeding of 10thCongress of the Hellenic Geographical Society, Thessaloniki, Greece, 2014*, pp. 1645–1652.