**Remote Sensing and GIS Analysis for Mapping Spatio-temporal Changes of Erosion and Deposition of two Mediterranean river Deltas: the case of the Axios and Aliakmonas rivers, Greece**

George P. Petropoulos1\*, Dionissios P. Kalivas2, Hywel M. Griffiths1, Paraskevi Dimou2

*1 Department of Geography and Earth Sciences, Penglais Campus, Aberystwyth, Aberystwyth University, SY23 3DB, United Kingdom*

*2 Department of Natural Resources Management & Agricultural Engineering, Agricultural University of Athens, 75 Iera Odos, 118 55, Athens, Greece*

\* Corresponding author: *George P. Petropoulos (*[*gep9@aber.ac.uk*](mailto:gep9@aber.ac.uk)*)*

ABSTRACT

Wetlands are among Earth’s most dynamic, diverse and varied habitats as the balance between land and water surfaces provide shelter to a unique mixture of plant and animal species. This study explores the changes in two Mediterranean wetland delta environments formed by the Axios and Aliakmonas rivers located in Greece, over a 25-year period (1984-2009). Direct photo-interpretation of four Landsat TM images acquired during the study period was performed. Furthermore, a sophisticated, semi-automatic image classification method based on Support Vector Machines (SVMs) was developed to streamline the mapping process. Deposition and erosion magnitudes at different temporal scales during the study period were quantified using both approaches based on coastline surface area changes. Analysis using both methods was conducted in a Geographical Information Systems (GIS) environment.

Direct photo-interpretation, which formed our reference dataset, showed noticeable changes in the coastline deltas of both our study areas, with erosion occurring mostly in the earlier periods (1990-2003) in both river deltas followed by deposition in more recent years (2003-2009), but at different magnitudes. Spatial patterns of coastline changes predicted from the SVMs showed similar patterns. In absolute terms SVMs predictions of sediment erosion and deposition in the studied area were different in the order of 5-20% in comparison to photo-interpretation, evidencing the potential capability of this method in coastline changes monitoring. One of the main contributions of our work lies to the use of the SVMs classifier in coastal mapping and changes, since to our knowledge use of this technique has been under-explored in this application domain. Furthermore, this study provides important contribution to the understanding of Mediterranean river delta dynamics and their behaviours, and corroborates the usefulness of EO technology and GIS in as an effective tool in policy decision making and successful landscape management. The latter is of considerable scientific and practical value to the wider community of interested users, given the continued open access to observations from this satellite radiometer globally.

# KEYWORDS: *remote sensing, GIS, Landsat TM, coastline mapping, photo-interpretation, Support Vector Machines, Axios, Aliakmonas, Greece*

# 1. INTRODUCTION

Changing land cover dynamics is regarded as the single most important variable of global change affecting ecological systems (Otukei and Blascke, 2010). Wetlands in particular, are among the most dynamic, diverse and varied habitats of the Earth, as the balance between land and water surfaces provides shelter to a unique mixture of plant and animal species. The various socio-economic activities (e.g. agriculture and fishing, tourism, conservation, urbanisation and resource extraction) that co-exist in such areas and the range of impacts linked to changes in these environments make regular monitoring imperative (Krestenitis et al., 2012). The environmental equilibrium and the bonds and interactions between different components of these systems are notably complex and fragile, and their functionality can easily be weakened or even lost.

In the Mediterranean in particular, both inland and coastal wetland environments are facing numerous problems. Major causes of concern include desertification, land degradation, the development of agriculture, livestock and fishing, decreases in river discharge due to climatic and anthropogenic causes, extensive drainage works, rural depopulation, urbanisation and pollution (Maragou and Montziou, 2000; Kalivas et al., 2003; Mallinis et al., 2011). These processes can cause erosion and deposition of sediment, which result in morphological changes that can directly impact the flora and fauna of these wetlands as well as the immediate environment of the people living in such areas.

A coastline is defined as the physical interface of land and water (Dolan et al., 1991; Gens, 2010). One way to identify changes in wetland ecosystems is by mapping coastlines which allows observing the way in which they have changed over different timescales. This is because knowledge of coastline position is the basis for measuring and characterizing land and coastal water resources (Liu and Jezek, 2004). Shifts in coastline position due to erosion and deposition are a major concern for coastal zone management as very dynamic coastlines can cause considerable hazards to human use and development (White and Asmar, 1999). Coastline mapping and quantification of coastline position changes are also essential for safe navigation, resource management, environmental protection, and sustainable coastal development and planning (Di et al., 2003). Also, many coastal habitats are designated as special areas of conservation under the EU Habitats Directive (Hadley, 2009). Thus, it is evident that rapid, replicable techniques are required to update coastline maps and monitor rates of movement (White and Asmar, 1999).

Earth Observation (EO) provides a very well-suited technology framework for habitats **mapping and monitoring. It** can provide data required by conservation initiatives such as **the EC Habitats Directive (Amarnath et al., 2003; Sanchez-Hernandez et al., 2007).** The general advantages of EO technology include its ability to provide inexpensive, continuous synoptic views at a range of spatial and temporal scales, even for inaccessible locations assuming data has been archived. Indeed, the detection of coastline changes using EO data has gained high importance over recent decades, since satellites are able to provide digital imagery in infrared spectral bands where the land–water interface can be well-defined (Ekercin, 2007**;** Durduran, 2010). Furthermore, EO data can be combined with Geographic Information Systems (GIS) to provide an effective set of tools for analysing and extracting spatial information to support reliable and consistent decision making (Bausmith and Leinhardth, 1997**;** Goodchild, 2001**;** Jaiswal et al., 2002**;** Chen et al., 2005; Durduran, 2010; Gens, 2010). This integration with EO datasets provides an excellent framework for data capture, storage, synthesis measurements and analysis, all of which are essential in coastline changes investigations.

Many studies have shown promising potential in providing an effective means of delineating coastlines and mapping their changes for different ecosystem conditions. For example, in China studies have been conducted in the Yellow River delta (Chu et al., 2006**;** Cui and Li., 2011), the Bohai Sea (Jiang, et al., 2003**;** Huang and Fan, 2004), the Fujian coast (Sun and Zhang, 2004) and the Pearl River delta (Li and Damen, 2010). Similar studies have also been conducted in river deltas in Santa Barbara, USA (Komar, 1998), Hualien, Taiwan (Hsu et al., 2000), Fortaleza, Brazil (Maia et al., 1998), Northeastern Nile Delta (White and Asmar, 1999) and Nouakchott, Mauritania (Wu, 2007). Notably, a few relevant studies have also focused on studying river delta changes in the Mediterranean (Kalivas, et al., 2003; Mallinis, et al., 2011; Krestenitis et al., 2012).

A recent overview of the current status of the use of EO technology for the detection, extraction and monitoring of coastlines can be found in Gens (2010). Generally, near-infrared and Synthetic Aperture Radar (SAR) images have been particularly useful for mapping coastlines as they provide the strongest contrast between land and water (Gens, 2010). Optical multispectral data have also been extensively used for this purpose. Manual photo-interpretation is regarded as one of the most commonly used techniques in the case when such EO data is used. Yet, in recent years a number of approaches have been proposed for extracting shorelines from EO data in a more automated fashion, with image classification being one of the most widely used (Gens, 2010). A review of the different classification approaches employed utilising EO data can be found in Lu and Weng (2007).

The rapid development of both remote sensors and hardware technology over recent decades has also opened up new opportunities for the EO community to exploit such data. A large amount of effort has been directed towards developing sophisticated image processing algorithms to be implemented with remote sensing data aiming to increase the accuracy with which coastline position can be extracted from satellite imagery (e.g. Pardo-Pascual et al., 2012; Zhang et al., 2013). This also places greater emphasis on the requirement for performing validatory and comparative studies assessing the performances of these newly-developed against traditional approaches (e.g photo-interpretation, supervised classifiers such as Maximum Likelihood Richards, 1999). In this context, and in view of the importance of river delta wetland environments outlined earlier, the capability of such contemporary image processing techniques with respect to coastlines extraction and monitoring needs to be evaluated.

Support Vector Machines (SVMs, Vapnik, 1998) in particular, is a supervised classifier that has several advantages in comparison to other hard classification approaches (for an overview of SVMs use see Mountrakis et al., 2011). SVMs implementation is not **based on any assumption regarding the probability distribution of the training datasets as it is done by parametric classifiers (e.g. Maximum Likelihood); SVMs obtain their decision directly from the training data in a suitable space that is described by a kernel function. In addition,** they are able to deal easily with high dimensionality datasets and have proven to effectively address ill-posted problems often providing high classification accuracies. Furthermore, contrary to other methods (e.g. Object-based Image Analysis, OBIA) they are generally easy to implement **requiring limited user expertise and effort in their training, as essentially only a few parameters need to be adjusted by the user. Also, SVMs classifiers implemented so far in many classification problems using different types of EO data acquired at a variety of spatial scales (e.g. SPOT, MODIS, Landsat TM/ETM+) have generally produced reliable and promising results (**Huang et al. 2008; Otukei and Blaschke, 2010; Petropoulos et al., 2012a,b; Volpi et al., 2013). Nevertheless, to our knowledge, the applicability of SVMs classifiers in coastline extraction and change mapping in comparison to traditionally employed techniques remains ill-explored. As well as being of high methodological and theoretical value, an investigation of the SVMs applicability would also be of great interest if implemented in Mediterranean environments, due to the high importance of coastline changes to other natural phenomena such as desertification and land degradation in the region (Castillejo-Gonzalez et al., 2009).

In this context, this study presents an application of Landsat TM satellite data and GIS techniques to the study of coastline delineation and decadal changes in a highly dynamic and significant deltaic Mediterranean ecosystem formed by the Axios and Alkiamonas rivers, located in the Thermaikos Gulf, northern Greece. In particular, an integrated analytical method combining Landsat TM imagery analysis and GIS is used to quantify soil/sediment erosion and deposition rates in the two river deltas during the period 1984 to 2009 based on four “anniversary” Landsat images acquired during this period. Furthermore, a semi-automatic image classification based on SVMs is also developed to streamline the mapping process and evaluate the effectiveness of this technique for monitoring coastline changes in the studied region over a 25-year period.

**2. STUDY AREA & DATASETS**

**2.1. Study area**

The deltas of both the Axios and Aliakmonas rivers, two of the largest rivers in Greece, are located in the prefecture of Macedonia (Fig. 1). Both deltas are part of a larger complex of wetlands on the Thermaikos Gulf coast (which also includes the mouth of the Gallikos and Loudias rivers), located in the north-western part of the Aegean Sea. The wetland complex is of international importance, protected by the Convention of Ramsar (1971). Numerous rare and endangered species are found in the area, justifying the inclusion of the region as a site of a Specially Protected Area under the European Directive 79/409/EC and as a Site of Community Importance following the implementation of European Habitat Directive 92/43/EC (site code GR1220002, area 33,676 ha). The two rivers have also been included as eligible sites for the proposed NATURA 2000 network of the EC Habitats Directive, the implementation of which aims to propose a network of Sites of Community Importance and Special Areas of Conservation.

The Aliakmonas is the longest river in [Greece](http://en.wikipedia.org/wiki/Greece), with a total length of 322 km and a catchment area of 9,250 km2 (Poulos et al., 2009). It flows through the Greek [regions](http://en.wikipedia.org/wiki/Modern_regions_of_Greece) of [West Macedonia](http://en.wikipedia.org/wiki/West_Macedonia) ([Kastoria](http://en.wikipedia.org/wiki/Kastoria_(regional_unit)" \o "Kastoria (regional unit)), [Grevena](http://en.wikipedia.org/wiki/Grevena_(regional_unit)) and [Kozani](http://en.wikipedia.org/wiki/Kozani_(regional_unit)) regional units) and [Central Macedonia](http://en.wikipedia.org/wiki/Central_Macedonia) ([Imathia](http://en.wikipedia.org/wiki/Imathia" \o "Imathia) and [Pieria](http://en.wikipedia.org/wiki/Pieria_(regional_unit)) regional units) and into the [Thermaikos Gulf](http://en.wikipedia.org/wiki/Thermaic_Gulf) west of the delta of the [Axios](http://en.wikipedia.org/wiki/Vardar). The Axios is the longest river in the Former Yugoslav Republic of Macedonia (FYROM) and is also one of the largest rivers in [Greece](http://en.wikipedia.org/wiki/Greece). It is 388 km long, has a catchment area of 23,747 km2 (Poulos et al., 2000) and rises at [Vrutok](http://en.wikipedia.org/wiki/Vrutok), a few kilometers north of [Gostivar](http://en.wikipedia.org/wiki/Gostivar) in the FYROM. It passes through [Gostivar](http://en.wikipedia.org/wiki/Gostivar), [Skopje](http://en.wikipedia.org/wiki/Skopje) and into [Veles](http://en.wikipedia.org/wiki/Veles_(city)), crosses the [Greek](http://en.wikipedia.org/wiki/Greece) border near [Gevgelija](http://en.wikipedia.org/wiki/Gevgelija), [Polykastro](http://en.wikipedia.org/wiki/Polykastro) and [Axioupoli](http://en.wikipedia.org/wiki/Axioupoli), before emptying into the [Aegean Sea](http://en.wikipedia.org/wiki/Aegean_Sea) in [Central Macedonia](http://en.wikipedia.org/wiki/Central_Macedonia) west of [Thessaloniki](http://en.wikipedia.org/wiki/Thessaloniki) in northern Greece. The mean annual discharge of the Axios and Aliakmonas rivers is 158 and 73 m3s-1 respectively, with noticeable fluctuations from year to year (Poulos et al., 2000). Karageorgis and Anagnostou (2001) noted that overall annual mean freshwater discharge to the delta from the Axios, Aliakmonas and Gallikos rivers decreased from 276 m3s-1 between 1926 and 1970 (Therianos, 1974) to 130 m3s-1 in 1997-1998, due to increased consumption by agriculture and urban development (Kapsimalis et al., 2005). The nutrients of these rivers provide the basis for a rich food chain and consist of important habitats for wildlife. Agricultural activity in the Axios and Aliakmonas delta is also intensive and as such the area is economically important. Rice production in the Axios and Alkiamonas deltas together account for approximately 60% of total Greek production and shellfish farming activity in the area comprises 85% of the total Greek shellfish output. Historical and contemporary anthropogenic activities - mainly dam building, river regulation and water abstraction for irrigation, - have led to the trapping of sediments and nutrients in dams preventing them from reaching the river deltas. Due to their highly dynamic nature and ecological and economic significance, these deltas provide an ideal location to both evaluate the potential capability of contemporary image processing algorithms to monitor coastal erosion and deposition, and to use the results in practical and valuable environmental management.

**2.2. Datasets**

Landsat TM images (path: 182, row: 34) were exploited to map coastline changes in the study region over a period of 25 years (1984-2009). Landsat data are the only multispectral satellite data available at no cost providing a synoptic coverage of the Earth extending back to 1972. Therefore, Landsat data have a unique value and this explains why their use has been extensively investigated for a variety environmental monitoring purposes, including coastline changes (e.g. Durduran, 2010; Yang et al., 1999; Thampanya et al., 2006; White and Asmar, 1999; Li and Damen, 2010; Cui and Li., 2011). In this study, TM images acquired on the 26th July 1984, 11th July 1990, 16th August 2003 and 31st July 2009 were used. This is because change detection requires multi-date cloud-free images around the same dates of the year or rather ‘anniversary dates’ (Lillesand and Kiefer 2000; Wu, 2007). This limits the effect of natural seasonal variations in spectral radiation surface reflection, phenological differences, as well as the semi-diurnal tidal effect of the area (Savvidis et al., 2005). As such, only cloud-free anniversary dates satisfying these conditions were used in our analysis, and all other dates omitted. This ensured that errors relating specifically to coastal regions (e.g. seasonal changes in sea-level, river discharge and vegetation) were minimised as much as possible and that the length of the time periods used for analysis are unequal. Tidal and fluvial variations in inundation extent could influence the extent of the areas mapped as land or water (and hence the estimates of erosion and deposition). However, the essentially low powered waves associated with the tideless Greek waters (Tsimplis, 1994. Kapsimalis et al., 2005) suggest that tidal variations will not greatly influence the accuracy of results. Variations in river discharge are more problematic, but as both rivers are heavily regulated and the frequency and magnitude of their peak flows reduced as a result, extreme variations in discharge are not thought to greatly influence mapping accuracy. All TM images used were obtained from the United Stated Geological Survey (USGS) archive (http://glovis.usgs.gov/). They were acquired at Level-1T processing, meaning that they were already geometrically corrected, geometrically resampled, and registered to a UTM 34N WGS84 ellipsoid with elevation correction applied.

# 3. COASTLINE DELINEATION AND EROSION/DEPOSITION ESTIMATION

A direct digitisation approach based on image photo-interpretation was used to extract changes from the EO data at different dates for the two river deltas. In addition, a supervised image classification approach was used to streamline the mapping process. This analysis will be discussed in detail in section 3.2. An overview of the methods used to address the objectives of our study is summarised in Fig. 2. The procedures for pre-processing the data are described next, followed by the description of the coastlines extraction methods and analysis approach.

**3.1 Pre-processing**

All pre-processing and geospatial analysis of the spatial datasets were carried out using ENVI (v. 5.0, ITT Visual Solutions) image analysis software. First, the TM images were imported into ENVI and were converted to radiance values (Irons, 2011). Subsequently, for each set of satellite imagery all the sensor spectral bands except the thermal infrared band (i.e. band 6) were layer stacked to form a single image file corresponding to the acquisition date of the dataset. Then an empirical line normalisation to all images was implemented using the 1984 image as a base (ENVI User's Guide, 2008). This is a relative atmospheric correction method used to relatively match the atmospheric effects which provides an easy way to correct for radiance/reflectance variations due to solar illumination condition, phenology and detector performance degradation (Latifovic et al., 2005). No further correction for topographic effects was necessary since images were already terrain-corrected.

Subsequently, image to image co-registration between the TM images was performed. The geometric registration process was also carried out in ENVI. In order to analyse EO imagery from different dates, the data layers must be spatially co-registered so that satellite data are in the same spatial reference frame (Schmidt and Glaesser, 1998). The TM image of year 1984 was used as reference image to which all other available images were co-registered. Approximately 45 commonly identified ground control points (GCPs) were selected based on random sampling from easily detectable corner points (e.g. road junctions). Positional root mean square error (RMSE) was kept below one pixel (i.e. 30 m of Landsat TM imagery) in both x and y dimensions while georeferencing. Image warping was performed by applying the nearest neighbour method, allowing a co-registration of all the images into a common UTM 34N projection under a WGS84 ellipsoid. This resampling method was used to better preserve the digital number (DN)/reflectance values in the original images. Finally, an image subset was selected covering an area which included the boundary of each river delta to enhance the computational efficiency of the processing that would follow.

**3.2 Coastline area mapping**

The following section describes in detail the steps taken in extracting the coastlines from our satellite imagery using the two approaches employed, namely the direct digitisation via the photo-interpretation of the acquired Landsat images and the semi-automatic SVMs-based supervised classification.

***3.2.1 Coastlines mapping based on image photo-interpretation***

Direct digitization of coastlines based on photo-interpretation of aerial or satellite imagery is regarded as one of the most commonly used approaches in extracting coastlines from EO data. Numerous studies have been implemented exploiting different types of EO data with this approach aiming to map coastlines and quantify changing environments in river deltas (Prabhakara-Rao et al., 1985; Li and Dammen, 2010; Durduran, 2010). Some of these studies have exploited Landsat TM data for this purpose (White and Asmar, 1999; Cui and Li, 2011; Vanderstraete et al., 2006; Li and Damen, 2010).

In order to extract the coastline from each image the visible bands of satellite data (RGB 3-2-1 true colour composite) were used for a first reconnaissance. To improve extraction of coastlines, RGB bands 7 (2.08 - 2.35 μm), 4 (0.76 - 0.90 μm), and 2 (0.52 - 0.60 μm) were the most effective for separation between land and water and composition of bands 4 (0.76 - 0.90 μm), 3 (0.63 - 0.69 μm) and 2 (0.52 - 0.60 μm) were most effective for vegetation. This is in agreement with other researchers also using TM data for coastlines mapping (e.g. Li and Dammen (2010). These principles were used in directly digitising the coastline from the pre-processed Landsat TM images.

***3.2.2 Semi-automatic coastlines delineation using SVMs***

Alongside the direct digitization, automatic image classification using the Support Vector Machines (SVMs, Vapnik, 1998) was also implemented to evaluate the ability of this technique to map areal changes in coastal environments in a more streamlined way. Support Vector Machines (SVM) are a non-linear and non-parametric large margin classifier implementing Vapnik's structural risk minimization principle (Vapnik, 1995; Schölkopf and Smola, 2002). SVMs separates the samples of different classes by finding the separating hyperplane related to maximal margin minimizing the hinge loss function (Boser, 1992). Such solution guarantees a minimal generalization error. By using non-linear kernel functions (e.g. Gaussian RBF, polynomial) the SVMs implicitly work linearly in a higher dimensional space, corresponding to a non-linear solution in the input space, where the data naturally lives. Such mapping into the higher dimensional kernel space is implicitly performed by applying a kernel function *k*(·,·), evaluating the dot product between samples mapped in some higher dimensional space as φ(xi)'φ(xj), where ' denotes vector transpose (Schölkopf and Smola, 2002). For the standard binary SVMs formulation implemented in this paper, the hyperplane *f*(x) = w'x + *b* optimally separating the two classes is found by minimizing:

The slack variables ξ allow some training errors, guaranteeing robustness to noise and outliers. C corresponds to a user selected parameter to control the complexity of the model, acting as a trade-off parameter between non-linearity and number of training errors. This quadratic optimization is solved by introducing Lagrange multipliers α to obtain the following dual form:

When the optimal solution of the latter optimization is found, i.e. the *α*, labels of unknown samples xt are predicted by the side of the margin in which they lie, i.e. by the following expression:

Note that standard SVMs are sparse in the *α* coefficients, so the final solution may be equivalently expressed only by the samples having a non-zero α. These samples are the ones lying on the separating margins *f*(x) =1 and *f*(x) =-1. In order to represent more complex hyperplane shapes than the linear examples, the techniques can be extended by using kernel functions. In this case, the problem transforms into an equivalent linear hyperplane problem of higher dimensionality. The use of the kernel function essentially allows the data points to be classified to spread in a way that allows the fitting of a linear hyperplane. SVMs also introduces a cost parameter C to quantify the penalty of misclassification errors in order to handle non-separable classification problems.

Herein, SVMs was implemented on each of the pre-processed TM images and at the original images spatial resolution (i.e. 30m) in three steps. First, a binary classification scheme was formulated, consisting of the classes "land" and "water”. This scheme was selected in order to match the study objectives and was also in accordance with approaches followed previously in other analogous studies (e.g. Thampanya et al., 2006; Chen et al., 2005). Second, training pixels representative of each class were collected separately from each of the TM images based on a random sampling strategy. Training points were selected directly from the TM images based on photo-interpretation and also using Google Earth high resolution imagery for assistance. In the third step, multi-class SVMs pair-wise classification was implemented in ENVI. SVMs was then applied using all the sensor reflective bands to define the feature space. The RBF kernel function was used for performing the pair-wise SVMs classification. This kernel requires the definition of only a small amount of parameters to run and has also already been shown to produce generally good results in a range of classification studies (e.g. Kavzoglu and Colkesen, 2009; Petropoulos et al., 2010; 2011; Yang, 2011). RBF kernel is defined from the following equation:

Radial Basis Function:  (4)

Parameterisation of the kernel was based on values given by other studies where SVM had been performed using TM data. Kernel parameterisation recommendations provided in the ENVI software User’s Guide (ENVI User’s Guide, 2008) were also taken into account. The *γ* parameter is a user-defined parameter and was set to a value equal to the inverse of the number of the spectral bands of the imagery used each time (i.e. in our study 0.111). In order to ensure accuracy the penalty parameter, which controls the trade-off between allowing training errors and forcing rigid margins, was set in to its maximum value (i.e. 100). The pyramid parameter was set to a value of zero, meaning that each image should be processed at full resolution. A classification probability threshold of zero was applied forcing all image pixels to be classified into one class label.

***3.2.3 Coastline change and erosion and deposition estimation***

A vector analysis approach was used in ArcMap GIS platform (ESRI, v. 10.1) to quantify the deposition and erosion amounts at different temporal scales during 1984-2009 using standard GIS processing capabilities (e.g. clip, union, erase). In particular, the surface change rates for the individual periods from 1984 to 1990, 1990 to 2003, 2003 to 2009 and 1984 to 2009 were quantified based on the coastline surface area changes (in km2) compared to the initial 1984 shoreline. Distances and areas of deposited and eroded sediment along the shoreline were then measured between the image acquisition dates. Negative values were interpreted as erosion, positive values as deposition and zero values as stable areas, in agreement to analogous studies conducted previously elsewhere (e.g. Chu et al., 2006). This allowed us to compare the estimates between the two datasets, after performing a simple raster data to vector conversion of the coastline classification maps derived from the SVMs implementation. It was then possible to coarsely quantify the magnitude of deposition and erosion and geomorphological evolution along the normal direction of the coastline measured by each by each method. Analogous approaches have been implemented in similar studies earlier (e.g. Wu, 2007; Durduran, 2010).

# 4. RESULTS AND DISCUSSION

**4.1. Changes in the two river deltas coastlines mapped by photo interpretation**

Coastline vector maps (Figures 3 and 4) show areas of erosion (in red) and deposition (in green) for the Axios and Aliakmonas river deltas respectively, for all four time intervals and for both approaches for extracting coastlines adopted in our study (i.e. photo interpretation and SVMs). Figures 5 and 6 show the total areas (in km2) and percentage of eroded (red) and deposited (green) land for the Axios and Aliakmonas, respectively, and Table 1 gives lists the magnitudes of erosion and deposition observed. Figures 3 and 4 show that the coastline along the entire two deltas changed considerably between 1984 and 2009. The reference data set obtained from photo-interpretation indicates that, in general, erosion has been the dominant process operating in the Axios delta between 1984 and 2009 and has been most intense around the outfall of the principal river channel. However, the balance between erosion and deposition within this period has been variable. Between 1984 and 1990 both erosion and deposition occurred along the river channel and in the coastal sections of the study site. Figure 5 shows that net sediment deposition took place during this period. Between 1990 and 2003, it is clear that erosion was by far the dominant process with very small areas of deposition evident along the main river channel. In the latest time period (2003-2009), the overall trend reverted to net deposition with small areas of erosion evident at some specific locations. Table 1 shows that between 1984 and 2009 the total erosion and deposition reached magnitudes of 1.488 km2 and 0.226 km2 respectively. However, care must be taken when interpreting results in this way. Our decision to focus on data from available anniversary dates rather than use all the data available did ensure that we minimised error in erosion and deposition estimation. Yet, during the long time periods between these anniversary dates compensating cycles of erosion and deposition are likely to occur, thus the true magnitude of erosion and deposition is underestimated (James et al., 2012).

Figure 4 indicates that sediment dynamics in the Aliakmonas river delta broadly correspond to that of the Axios river delta. Clearly, between 1984 and 2009, erosion seems to have been the dominant process although this erosion seems to have been concentrated along the coastal areas, rather than along the principal river channel. Extensive areas of deposition are evident along the banks of the main channel during this period. Similarly to the Axios river the patterns of erosion and deposition within this time period are variable. Between 1984 and 1990 extensive areas of deposition are evident both in coastal areas and along the main river channel. Figure 6 shows that net sediment deposition occurred during this period. Again, similarly to the Axios river, erosion was by far the dominant process between 1990 and 2003. Analysis of Figure 4 shows that deposition during this time period was concentrated along the main river channel, with the majority of erosion taking place in the coastal areas. Once again, in the final time period (2003-2009), deposition was the dominant process with a few small areas of erosion only evident along the eastern coastal area of the study site. Table 1 shows that between 1984 and 2009 the total areal extent of sediment eroded from this site was 0.933 km2 compared to 0.309 km2 of land deposited. In summary, therefore, the morphological and sedimentological dynamics of the Axios and Aliakmonas river deltas between 1984 and 2009 can be characterised as net deposition between 1984 and 1990, followed by a greater magnitude of net erosion between during the longest time period (1990-2003). The latter was followed by a subsequent reversion to net deposition between 2003 and 2009. Figure 7 compares the magnitude of net erosion and/or deposition evident in both the Axios and Aliakmonas river deltas during each time period. While the magnitudes of deposition are relatively similar between both catchments in 1984-1990 and 2003-2009 - although deposition was greater in the Aliakmonas during the latter period - the magnitude of erosion displayed both in 1990-2003 and during the entire study period (1984-2009) is evidently suggested to be higher in the Axios river.

The accuracy of these measurements depends on the spatial resolution of the source data, in our case of Landsat TM. Generally, the higher the spatial resolution of the sensor, the higher the accuracy of the detected coastline (Gens, 2010). Yet, in our study, possible error sources in the estimates of coastline changes and in the magnitude of erosion and deposition can be related to inaccuracies in the manual delineation of coastlines, the registration error and other systematic errors. However, even collectively, these were not thought to constitute a significant source of overall error relative to the study objectives. This is because the calculated synthetical error is about one pixel when delineating coast information in a flat coastal zone (Huang et al., 2002; Chu et al., 2006), which is a small error relative to the magnitude of the overall changes in our study area.

**4.2. Coastline changes mapping by SVMs**

The relative accuracy of the SVMs’ delineation of coastlines from TM imagery and mapping of magnitudes of erosion and deposition has been evaluated based on the comparison between the algorithm-derived predictions and the corresponding estimates derived from visual interpretations of the original satellite images.

As seen from Figure 5, coastline prediction by SVMs is not in close agreement with the reference method of photo-interpretation in terms of identifying whether net erosion or deposition took place in the Axios river delta between 1984 and 1990. SVMs results indicate that net erosion, rather than deposition occurred during this period. However, there is an agreement between the SVMs and photo-interpretation methods in terms of the magnitude of erosion that has taken place. In contrast, between 1990 and 2003 the SVMs results are in agreement with the photo-interpretation in that it shows net erosion in the area. This agreement between the two methods is once again seen between 2003 and 2009 and there seems to be some degree of agreement regarding the magnitude of deposition observed by both methods. Over the entire time period of analysis (1984-2009) there is agreement between SVMs and the photo-interpretation method, both indicating that net erosion took place. On both rivers, between 2003 and 2009 the surface areas of erosion and deposition calculated by the two methods are, in general, lower than for 1984-1990 and 1990-2009. The surface area of sediment eroded in 1990-2003 was also markedly greater than for other time periods. This could be related in part with the fact that this time period is the longest of all three time periods, rather than reflecting increased rates of erosion. It is possible that if this long time period was sub-divided into shorter time periods of the same length as the other time periods that the area of sediment eroded would be lower, and/or that more of the short-term variability (i.e. alternating period of erosion and deposition) would have been captured.

The results obtained for the Axios river delta are also largely mirrored in the Aliakmonas river delta, in that there is lack of agreement between SVMs and photo-interpretation for the period 1984-1990. For all other periods, there is agreement between SVMs and photo-interpretation in that the nature of the sediment dynamics (erosion or deposition) is correctly identified, although there are differences in terms of the magnitude of these processes. For example, for the periods 1990-2003 and 1984-2003, SVMs seems to have over-estimated the erosion that has taken place on the Aliakmonas (Figure 6), whereas SVMs have underestimated the magnitude of erosion that has taken place on the Axios during the same time periods (Figure 5) when compared to photo-interpretation.

Extensive visual comparison between the two datasets shows that the relative accuracy of the algorithm-derived coastline is generally within one or two image pixels compared with visual interpretation of coastline features. Although the magnitudes of erosion and deposition vary between methods both methods are generally in agreement as to whether the delta is experiencing net erosion or net deposition. However, different estimates in absolute terms were obtained between the methods in estimating the total magnitudes of erosion and deposition and in some cases in the trends of coastline change (Figure 7, Table 1). Differences in the estimates by SVMs may possibly be attributed to the different operational procedures and principles underlying the implementation of the method in comparison to photo-interpretation. SVMs attempt to classify every single pixel in a satellite image by trying to produce an optimal separating hyperplane for separating classes. Also, as a hard classifier, SVMs does not operate on a sub-pixel level, which can theoretically significantly reduce the accuracy of those classifiers especially when applied with coarse spatial resolution data. The latter can be even more significant in areas with high degree of land use/cover fragmentation and heterogeneity that exists in Mediterranean ecosystems such as our study site.

**4.3 Possible drivers of coastal change in the two river deltas**

Analysis of photo-interpretation results indicates that although the Axios and Aliakmonas river deltas have eroded between 1984 and 2009, net deposition was evident between 1984 and 1990 and between 2003 and 2009, with the majority of erosion occurring in the period 1990-2003. Sediment dynamics in alluvial rivers in particular can be influenced by both climatic and anthropogenic factors by impacting sediment delivery through land cover and vegetation, the frequency with which sediment entrainment and erosion thresholds are crossed, and the sediment transport capacity of rivers. Anthropogenic activities such as dam construction, in-stream gravel extraction and channelization can all significantly influence how sediment is supplied to, and transported by, river systems. In common with other Greek rivers, the discharges of the Axios and Aliakmanos rivers have seen significant changes due to both climatic and anthropogenic factors during the past 40-45 years. It is estimated that the discharge of the Axios River has decreased by 57 % (Sabater and Tockner, 2010) and is currently regulated by a series of 13 dams (Poulos et al., 2000) and the Aliakmonas has been similarly impacted by increased variations from typical values due to regulation by four dams (Poulos and Chronis, 1997; Krestenitis et al., 2012). In terms of climatic changes, Karageorgis et al., (2005) noted that there was a period of high discharge on the Axios between 1980 and 1985, followed by a period of low discharge between 1988 and 1994 and a period of relatively higher discharge between 1995 and 2000. This was proportional to variations in precipitation. The first period of deposition observed on both rivers, therefore, occurred during a period of predominantly high discharge. After discharge decreased during 1988-1994, erosion became the dominant trend, continuing into the period of higher discharges after 1995.

However, it is very difficult to unpick the relative impacts of synchronous climatic and anthropogenic factors. The Axios and Aliakmonas rivers are two of the most severely modified rivers in this region of Europe (Tockner et al., 2010). Both systems have been extensively regulated by dams, and in common with other rivers in Europe (Liébault and Piégay, 2001; Kondolf et al., 2002; Surian and Rinaldi, 2003; Gittins, 2004; Surian et al; 2009) and beyond (Williams and Wolman, 1984; Kondolf, 1997), the impact of regulation on catchment-scale sediment dynamics seem to have been severe. The retreat of the shoreline of the Axios and Aliakmonas river deltas over the second half of the twentieth century has been described by Athanasiou (1990), Zalidis et al., (2007), Smardon (2009) and Kapsimalis et al., (2005). The erosion noted by our work is part of a longer term trend found by Athanasiou (1990) who noted that approximately 5.25 km2  of the Axios delta was lost between 1945 and 1970 due to erosion and subsidence. The findings of this paper also confirm the findings of Zalidis et al., (2007) who found that the surface areas of the Axios delta characterised by water increased by 13.6 % during the 1990s and early 2000s. As Kapsimalis et al., (2005) noted this is very likely to have been a result of channelisation, land reclamation and regulation. Dams in both river catchments have disrupted their natural discharge regime and sediment dynamics by decoupling the upper reaches from the deltaic regions, thus reducing the volume of sediment reaching those coastal areas. In addition, over-abstraction of water from aquifers to provide Thessaloniki with water has exacerbated the reduction in discharge (Poulos et al., 2000). The influence of these anthropogenic activities on the geomorphology of the deltaic regions is compounded by the fact that the influence of the fluvial component of the system is much greater than that of the oceanic component. The deltas of both rivers are subject to lower monthly wave power compared to the neighbouring Pinios river delta and the fact that the monthly distribution of high discharge and high wave action do not coincide is interpreted as that the waves are not powerful enough to redistribute river-borne sediment (Poulos et al., 2000). The impacts of decreases in both discharge and sediment load in the rivers will, therefore, be particularly evident. This paper has focused on coastal changes in the delta of the Axios and Aliakmonas rivers, however, changes in other rivers that also drain into the Thermaikos Gulf (especially the Galliakos) should also be considered. Given that anthropogenic pressures such as aggregate extraction for construction also affects these rivers, changes here may affect geomorphological processes in the wider coastal region. The response of these deltas to anthropogenic activities is in common with other landscapes in Greece such as the Kotychi lagoon (Kalivas et al., 2003) and Nestos delta (Mallinis et al., 2011).

Trajectories of geomorphological change in these catchments may be more complex than simply delta erosion due to reduced sediment and discharge load and may display complex response where the systems respond to one perturbation by oscillating between different modes (e.g. erosion and deposition - Schumm, 1973). Damming of the Axios and Aliakmonas could have led to erosion in downstream reaches, including the deltas because of sediment starvation and increased clear water erosion of river beds and banks. In theory, this could have been compounded by increased unit stream powers in straightened, channelized reaches. Subsequently, this may have led to periods of deposition as the sediment released by the clear water erosion is delivered to downstream reaches. As a result of the significantly reduced discharges due to climatic changes, increased water abstraction and decreased high flows due to regulation, the transport capacity of these rivers would have been reduced leading to deposition. As well as possibly displaying a general response to river regulation, the main channel of the Aliakmonas river delta may also be responding to channelization by narrowing. This is in common with many other rivers across Europe which have been extensively modified during the second half of the twentieth century (e.g. Winterbottom, 2000; Surian and Rinaldi, 2003; Surian et al., 2009). The erosion rates of the coastlines, deltaic regions and wetlands exhibited here are in common with other examples across the world, which are also in response to increased anthropogenic impacts in their catchments (e.g. the Nile delta – White and El Asmar, 1999, the Yellow River – Chu et al., 2006; Cui and Li, 2011 and drylands in southern Africa – Tooth and McCarthy, 2000).

The variation in sediment dynamics between the entire period and the individual time periods not only indicates that the sediment dynamics may change as a result of climatic or anthropogenic influences, but also that surveys are required at a higher temporal resolution in order to accurately characterise the nature, magnitude and rates of sediment movement. Although it is clear that erosion has been the dominant process during the longest time period (1990-2003) this may mask short-term periods of deposition (i.e. compensating change) that may have occurred over annual periods. However, as previously described, using data from non-anniversary dates from intervening years would have compromised the accuracy of the erosion and deposition estimation and we believe that although shorter time periods would be more informative, this analysis does provide valuable information on long-term (decadal) trends. Similarly, analysis of more EO data (e.g Landsat 8) in future is necessary in order to accurately ascertain whether the deposition evident in the latest period (2003-2009) does, in fact, represent a permanent shift to a period of sediment deposition, or whether it is a short-term period of deposition within the longer term trend of shoreline and delta retreat observed by this study and others (e.g. Mallinis et al., 2011). In addition, this study is limited by the fact that only two dimensional changes have been investigated. Further work on these deltas will be interesting if it is focus on integrating remotely sensed data such as Landsat with either terrestrial (e.g. the work of Milan et al., 2007 and Williams et al., 2011, 2013) or airborne (e.g. Lane et al., 2003 and Westaway et al., 2003) laser scanned or photogrammetric topographic data in order to more accurately characterise morphological changes in these hugely significant ecological landscapes. These three dimensional data would also allow the production of probabilistic maps of elevation change (e.g. Wheaton et al., 2010).

# 5. Conclusions

This study demonstrated the usefulness of EO technology and GIS techniques for the analysis of the spatio-temporal dynamics of coastlines in the river deltas formed by the Axios and Aliakmonas rivers of the Thermaikos Gulf, northern Greece. In addition to direct photo-interpretation which formed our reference dataset, a sophisticated, semi-automatic, classification technique based on SVMs was implemented to evaluate its ability to extract information about the morphological changes that have taken place in this dynamic coastline, and if this process could be streamlined.

Our analysis results based on both methods suggested that extensive erosion and shoreline retreat occurred in both the Axios and Aliakmonas river deltas between 1984 and 2009. Photointer-retation results suggested erosion to be occurring for both river deltas in mostly in the earlier periods (1990-2003) followed by deposition in more recent years (2003-2009), but at different magnitudes detectable at the Landsat TM pixel used in our study. This degradation which has occurred during the past ~ 25 years is seen to be primarily a result of decreased discharges and disrupted sediment dynamics due to extensive river regulation and irrigation.SVMs-based coastline changes mapping showed similar trends in terms of patterns in erosion and deposition for the same periods, yet, at a magnitude different in the order of 5-20% in comparison to photo-interpretation. The latter evidencing the potential capability of this method in coastline changes monitoring when used synergistically with EO datasets sucha s Landsat.

The international significance of this study lies to the exploration and to the demonstration of the SVMs technique capability when used synergistically with freely distributed EO data to provide potentially a cost-effective, rapid and accurate solution in coastline changes management. The latter, can be of vital importance to policy decision making and successful landscape management. In addition, this study provides an important contribution to the understanding of Mediterranean river deltas dynamics. The latter is of critical importance, given the increasing pressures in respect to climatic extremes, anthropogenic activities of various forms and continued conflicts between economical and conservational land-use practices. As at present systematically are acquired from space at a global scale distrubuted EO data from the Landsat series, this is of considerable scientific and practical value towards the support of sustainable environmental development and prudent resource management of our planet. Yet, a succesful coastlines management and changes interpretation, requires EO data to be supported by ancillary information related to factors whch might be responsible for triggering changes erosion and deposition dynamics in a a coastal environment, including both anthropogenic activities and/or natural hazards events.

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