

MAPPING EROSION AND DEPOSITION CHANGES IN THE PROTECTED WETLANDS OF THE AXIOS RIVER DELTA, N. GREECE USING REMOTE SENSING AND GIS

Griffiths H.M.¹, Kalivas D.P.², Petropoulos G.P.¹ and Dimou P.²

¹ Institute of Geography and Earth Sciences, Llandinam Building, Penglais Campus, Aberystwyth University, Aberystwyth, Wales, UK, SY23 3DB, hmg@aber.ac.uk, gep9@aber.ac.uk,

² Geographical Information Systems Research Unit, Department of Natural Resources Management & Agricultural Engineering, Agricultural University of Athens, 75 Iera Odos, Athens, GR-118 55, kalivas@aua.gr, e_vi_dim@hotmail.com

Abstract

Our study explores the use of a range of image processing methods combined with Landsat TM imagery for mapping the morphodynamics of the delta of the Axios River, one of the largest rivers of Greece, between 1984 and 2009. The techniques evaluated ranged from the traditional spectral bands arithmetic operations to unsupervised and supervised classification method. Changes in coastline morphology and erosion and deposition magnitudes were also estimated from direct photo-interpretation of the TM images, forming our reference dataset. Our analysis, conducted in a GIS environment, showed noticeable changes in the coastline of the study area, with erosion occurring mostly in the early periods followed by deposition later on. In addition, relatively similar patterns of coastline change were obtained from the different approaches, albeit of different magnitude. The differences observed were largely attributed to the varying ability of the different approaches to utilise the spectral information content of the TM data, strongly linked to the relative strengths and weaknesses underlying the implementation of the different techniques. Notably, supervised classifiers based on machine learning showed the closest results to the photo interpretation of TM, evidencing a promising potential for monitoring shoreline changes over long timescales in a cost-effective and rapid manner.

Keywords: coastal, Landsat, estuary, fluvial, sediment.

Περίληψη

Στην παρούσα εργασία γίνεται χρήση διαφορετικών μεθόδων επεξεργασίας δορυφορικών εικόνων Landsat TM για την χαρτογράφηση των αλλαγών, μεταξύ 1984 και 2009, του Δέλτα του Αξιού ποταμού, ενός από τους μεγαλύτερους ελληνικούς ποταμούς. Οι χρησιμοποιηθείσες τεχνικές περιλαμβάνουν από τις παραδοσιακές αριθμητικές επεξεργασίες των φασματικών δεδομένων των διαφορετικών καναλιών, έως τις μη επιβλεπόμενες και επιβλεπόμενες μεθόδους ταξινόμησης. Αλλαγές στην μορφολογία της ακτογραμμής καθώς και στη διάβρωση και στην απόθεση υλικών εκτιμήθηκαν επίσης από άμεσες φωτοερμηνευτικές παρατηρήσεις στις TM εικόνες που χρησιμοποιήθηκαν. Η ανάλυση των δεδομένων, που έγινε σε περιβάλλον GIS, έδειξε σημαντικές αλλαγές στην ακτογραμμή της περιοχής μελέτης, με την διάβρωση να κυριαρχεί στα πρώτα χρόνια και στη συνέχεια να ακολουθεί η απόθεση υλικών. Επιπροσθέτως σχετικά ίδιες τάσεις αλλα-

γής της ακτογραμμής παρατηρήθηκαν σε όλες τις μεθόδους επεξεργασίας των εικόνων, διαφορετικού όμως μεγέθους. Οι διαφορές που παρατηρήθηκαν οφείλονταν κυρίως στην διαφορετική ικανότητα των μεθόδων να χρησιμοποιούν τις φασματικές πληροφορίες των TM δεδομένων, γεγονός στενά συνδεδεμένο με τα πλεονεκτήματα και μειονεκτήματα κάθε μιας μεθόδου. Σημαντικό είναι ότι επιβλεπόμενες ταξινομήσεις, βασισμένες σε αλγόριθμους εκπαίδευσης έδειξαν πιο παραπλήσια προς την φωτοερμηνεία αποτελέσματα, γεγονός που αναδεικνύει μια σημαντική δυνατότητα για την παρακολούθηση των αλλαγών των ακτογραμμών κατά τη διάρκεια μεγάλων χρονικών διαστημάτων με οικονομικό και γρήγορο τρόπο.

Λέξεις κλειδιά: ακτή, Landsat, εκβολές, ποτάμιες, ίζημα.

1. Introduction

Characterizing and measuring land and water resources in coastal regions is dependent on an accurate knowledge of the position of the coastline (Liu and Jezek, 2004). River deltas or estuaries are areas of transition between the riverine zone, dominated by fluvial processes and the estuarine zone where coastal processes driven by tidal and oceanic processes are dominant. They are complex, dynamic environments which can often be characterized as wetlands and as such, are significant ecological resources. The management and protection of these resources, safe navigation and sustainable coastal development and planning require accurate mapping of the coastline and change detection (Di et al., 2004).

To this end, Earth Observation (EO) data and image processing methods applied to such types of data have become increasingly important because they can provide digital imagery in infrared spectral bands where the land–water interface is well defined (Alemayehu et al., 2006, Alesheikhet al., 2007, Ekerin, 2007, Durduran, 2010). Furthermore, EO data can be integrated with Geographic Information Systems (GIS) as an effective tool for analyzing and extracting reliable and consistent information based on satellite imagery (Bausmith and Leinhardt, 1997, Goodchild, 2001, Jaiswal et al., 2002, Durduran, 2010). With reference to coastline changes mapping, EO data have been exploited to study coastline dynamics in the Yellow River delta (Yang, et al., 1999, Li et al., 2004, Chang et al., 2004, Chu et al., 2006, Cui and Li., 2011), the Bohai sea (Jiang, et al., 2003, Huang and Fan, 2004), Fujian coast (Sun and Zhang, 2004) the Pearl River delta (Li and Damen, 2010), Santa Barbara, USA (Komar 1998), Hualien, Taiwan (Hsu et al. 2000), Fortaleza, Brazil (Maia et al. 1998), the Northeastern Nile Delta, Egypt (Frihy et al. 1998, White et al. 1999), Nouakchott, Mauritania (Wu, 2007) and in Greece in particular on the Thermaikos Gulf (Zalidis et al., 2007) the Nestos delta (Mallinis et al., 2011) and the Kotychi Lagoon (Kalivas et al., 2003).

In Mediterranean countries such wetland areas face numerous problems: agricultural development, over-grazing of livestock, over-fishing, decreases in water discharge, drainage works, urbanization and pollution (Maragou and Montziou, 2000). In Greece in particular, the Axios River, one of the longest in Greece, as well as neighbouring rivers have been extensively modified during recent years and have been impacted by dam-building upstream. Despite these problems, the Axios River delta in particular is still of outstanding importance mainly because it performs functions such as trapping of river-borne sediment, nutrient removal, shoreline anchoring and food chain support. As well as being hugely important for wildlife it is economically important – agricultural activity in the Axios delta area is intensive. Rice production in the Axios and Alkiamnonas 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 (Karageorgis et al., 2005). Morphological changes caused by erosion and deposition of sediment directly impact the flora and fauna of these wetlands. These processes may be influenced by changes in anthropogenic activities upstream, but they may also reflect changes in climate. There is, therefore, a need to develop a greater understanding of the spatial and temporal dynamics of these areas over a range of temporal timescales in order to inform

the development of integrated catchment and coastal management plans to protect, improve and maintain the environment and improve the quality of group decision processes.

The aim of this paper is to characterize and quantify the changes in coastline position that have occurred at the delta of the Axios River on a decadal timescale. This has been achieved by analysis of four sets of Landsat TM data acquired in the area over a period spanning of ~25 years, using five different image processing techniques. Not only will this provide information on the nature, rates and patterns of change in the delta, but it will also provide valuable information on the suitability of these different image processing methodologies (supervised and unsupervised, machine learning etc) for the detection of geomorphological changes.

2. Materials and methods

2.1. Study Region

The delta of the Axios River is located in the prefecture of Macedonia, Greece (Figure 1). The river rises near Vrutok in the Scardos Mountains (Smardon, 2007) and is the longest river in the Former Yugoslav Republic of Macedonia (FYROM). It passes through Gostivar, Skopje and into Veles, crosses the Greek border near Gevgelija, Polykastro and Axioupoli, before emptying into the northwestern part of the Aegean Sea in Central Macedonia west of Thessaloniki, northern Greece. In total it is 388 km long, with the final 80 km in Greece. Its catchment area is 23747 km², 90 % of which is in the FYROM and has a mean annual discharge of 85 m³s⁻¹ but displays significant interannual variability (Albanis et al., 1994). The Axios River delta is part of a larger complex of wetlands on the Thermaikos Gulf coast which also includes the mouths of the Alkiamnonas, Gallikos and Loudias rivers protected by the Ramsar Convention (1971).

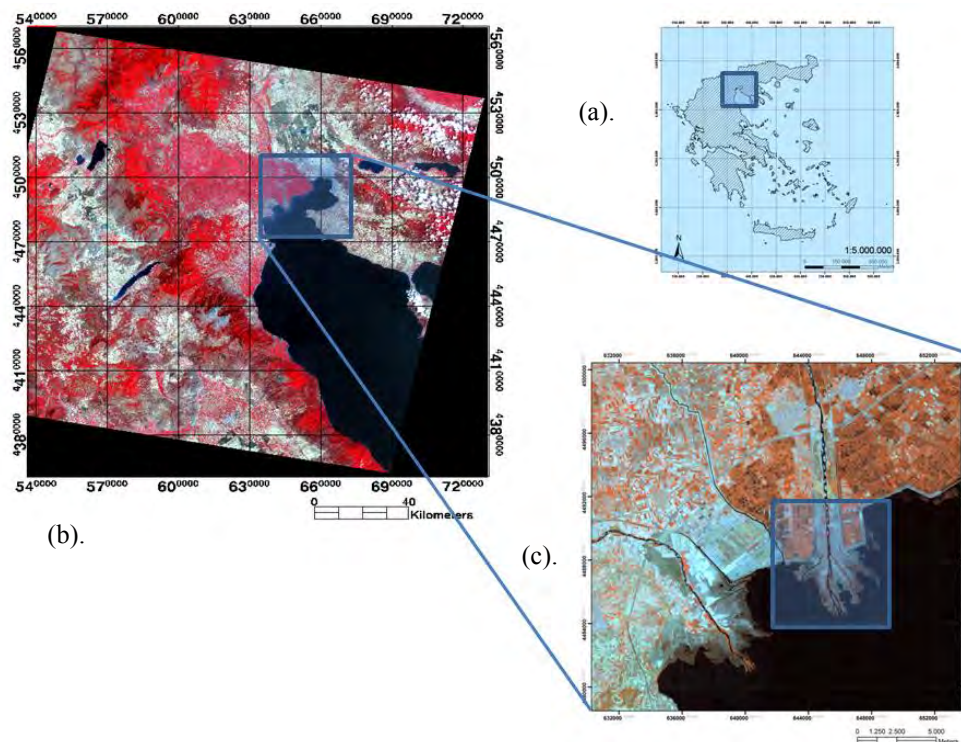


Figure 1 - (a): Location of the study area (B4G3R2); (b): an example of one of the Landsat TM images acquired over studied region shown in the square box (acquired on July 26th, 1984; B7G5R4); (c): the Landsat TM subset on which we focused our analysis in the present study.

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). The TM images were acquired on the 26th July 1984, 11th July 1990, 16th August 2003 and 31st July 2009. An example of one of the acquired TM images is shown in Figure 1b. All images were obtained from the United States Geological Survey (USGS) archive (<http://glovis.usgs.gov/>) at no cost. Images were provided geometrically corrected, geometrically resampled, and registered to a geographic map projection with elevation correction applied (Level-1T processing). Selection of the specific images was based on the fulfilment of criteria that included clear atmospheric conditions, high sun conditions, low water vapour, near-nadir viewing and acquisition seasonal temporal proximity in order to minimize effects of atmosphere and vegetation phenology. In addition, the global digital elevation model (GDEM) derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor was acquired. The ASTER GDEM product was released in 2009 and it was acquired as a “geotiff” image at geographic lat/long projection and WGS84/EGM96 datum from the NASA’s Land Warehouse Inventory Search Tool (WIST, <https://wist.echo.nasa.gov/~wist/api/imswelcome/>).

2.3. Methodology

TM images were imported to ENVI platform and were converted to radiance values as described in the Landsat 7 Science data users’ handbook for ETM+ (Irons, 2011). Subsequently, all the bands apart from thermal band 6 from each image were layer stacked to form a single image file corresponding to the various acquisition dates. Empirical line normalization was then applied to all three TM images to relatively match the atmospheric effects using the 1984 image as a base. No further correction for topographic effects was necessary since images were already terrain-corrected. Finally, image to image co-registration between the TM images as well as the DEM was performed. Approximately 20 ground control points (GCPs) commonly identified on both the reference and target images were manually selected at random. Positional root mean square (RMS) error was kept below one pixel (i.e. 30 m) in both x and y directions 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. Finally, an area of approximately 46 km² was subset around Axios River delta (Fig. 1c).

This step also increased computational efficiency of the different image processing techniques employed in our study for delineating the coastline and analysing the changes occurred. The resulting dataset for each image subset for each image acquired was subsequently used to extract the coastline each time via direct photo-interpretation and subsequently by performing different image classification. In particular, a coastline from each TM image was extracted based on the following semi-automatic techniques:

- Direct digitisation (photo-interpretation –bands 4,5,7 – e.g. Li and Damen, 2010)
- Band Ratio (TM2/TM5 – e.g Cui & Li, 2011)
- ISODATA unsupervised classification (Richards, 1999)
- Support vector machines (SVMs, Vapnik, 1998) and maximum Likelihood (ML) supervised classification (Richards, 1999).

Subsequently, coastline estimates from the different techniques applied were compared and erosion and deposition rates were estimated based on the coastline surface area (km²) changes during the years of analysis.

3. Results

Figure 2 shows the areas of erosion (i.e. those areas classified as land in the earlier image and as water in the later image) in red and the areas of deposition in green in the Axios river delta for all three time intervals for all five image processing methods used. Figure 3 presents the total areas (in

m²) of land being characterised as having been lost to erosion (red) and gained through deposition (green). As expected the erosion and deposition processes are proven to be more intense along the outfalls of the main river channels. Our reference data set obtained through photo-interpretation of the Landsat TM imagery indicates that the Axios delta has experienced net erosion between 1984 and 2009. Within this period, net deposition has taken place between 1984 and 1990; net erosion took place between 1990 and 2003, with a reversion to erosion between 2003 and 2009. Between 1984 and 1990, the magnitude of deposition was 474.59 km², between 1990 and 2003 erosion reached a magnitude of 1603.35 km² and deposition between 2003 and 2009 was 373.55 km². Between 1984 and 2009 the total erosion reached a magnitude of 1487.91 km².

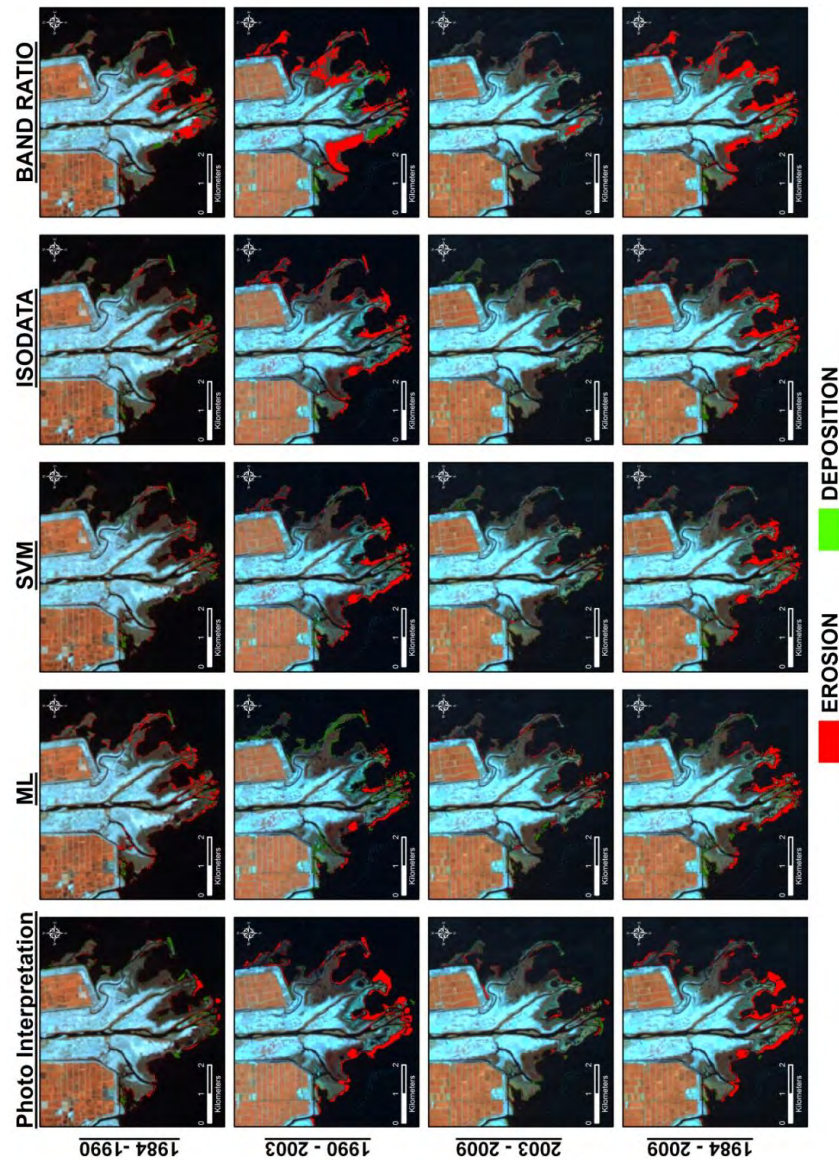


Figure 2 - Maps showing areas of erosion (red) and deposition (green) in the Axios River delta in 1984-1990, 1990-2003, 2003-2009 and 1984-2009 using five methods of analysis (photo interpretation, ML, SVM, ISODATA and Band Ratio). The background image is a false colour composite of the Landsat TM image (B7G5R4), with orange areas representing vegetated areas and blue representing bare earth.

The ISODATA method is in agreement with the photo interpretation method, but in contrast, ML, SVM and Band Ratio methods indicate that delta was experiencing net erosion between 1984 and 1990. Band Ratio recorded the largest area of land eroded (1232.71 km²) compared to the other methods. This area represented 5.41 % of the area classified as land in 1984. Although the photo-interpretation and ISODATA methods indicated that net deposition occurred during this period, there is generally good agreement between these methods and the SVM in terms of the surface area eroded. Between 1990 and 2003, erosion seems to be the dominant process in the delta, with SVM, Band Ratio and ISODATA methods all in agreement with photo interpretation indicating that the delta experienced net erosion. Indeed, the area of land eroded according to Band Ratio was 2273.59 km² (10.36 %) and all five methods indicated that the surface eroded during this period was higher than that which was eroded in 1984-1990. Of course, this could be due to the fact that 1990-2003 is a longer time period than 1984-1990 rather than that the rate of erosion has increased or that the rate of deposition has decreased. In contrast to 1984-1990, there is no agreement between ML and the other methods, with the former indicating that deposition was the dominant process.

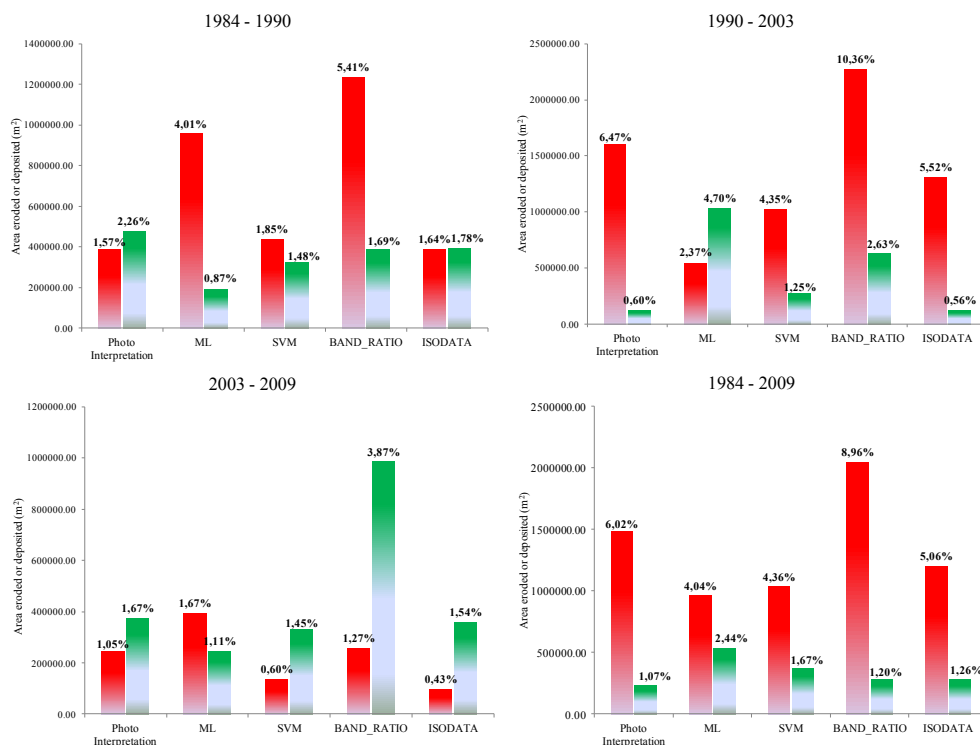


Figure 3 - Erosion (red) and deposition (green) in the Axios River delta for all time periods and for all methods.

Between 2003 and 2009 the surface areas of erosion and deposition calculated by the five methods are, in general, lower than for 1984-1990 and 1990-2009. Overall, the methodologies characterised this period as one in which net deposition occurred in the delta, with SVM, Band Ratio and ISODATA all in agreement with photo interpretation in this respect, whereas ML indicated net erosion. Once again, the Band Ratio method indicates the greatest magnitudes of deposition (984.86 km² or 3.87 %) compared to the other methods, which are markedly lower. Finally, analysis of the figures for the period 1984-2009 clearly shows that all methods are in agreement that the delta has eroded, although there are differences between methods regarding the magnitude of this process. There is good agreement between the ML and SVM methods in terms of the magnitude of erosion that has occurred (961.32 km² and 1032.42 km², respectively) while photo interpretation, Band Ratio

and ISODATA seem to correspond in terms of the magnitude of deposition (225.56 km², 275.46 km² and 278.46 km², respectively). Once again, Band Ratio has indicated the greatest magnitude of erosion during this period at 2042.52 km², indicating that 8.96 % of the surface characterized as land in 1984 had been eroded by 2009. A crude calculation would give an annual rate of 81.70 km², however it is clear from the results presented that the rate of erosion is not constant, with some periods displaying faster rates of erosion than others, and some periods displaying overall net deposition (2003-2009). This complexity is confirmed by Figure 4, which shows that, overall, the surface area characterized as land has decreased between 1984 and 2009, and that the surface area characterized as water has increased, there are fluctuations between each time period, with some methodologies showing an increase in land area followed by a decrease and vice versa.

4. Discussion

Analysis of the results of the photo interpretation method, which we may regard as the reference method, indicates that although the coastline of the Axios River Delta has 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. Many previous studies have noted that the Axios River delta has been subject to anthropogenically-driven degradation over the second half of the twentieth century. For example, Kapsimalis et al., (2005) noted that in contrast to the period 1916-1956 during which increased sediment load and delta progradation occurred as a result of channelisation, land reclamation, the coastline experienced significant retreat between 1956 and 2000. This was primarily due to a reduction in the delivery of sediment to the delta because extensive dam-building in the upper reaches of the Axios had trapped significant proportions of the river's load. In addition Athanasiou (1990) showed that approximately 525 ha of the coastal wetland were lost between 1945 and 1970 due to erosion and subsidence (Smardon, 2009). The findings of the present study also confirms those of a similar study by Zalidis et al., (2007) who showed, using EO data, that the surface area of the delta characterized as water had increased by 13.6 % between 1994 and 2004. The authors also attribute this pattern to the influence of dams and of decreasing river discharge at the delta, possibly as a result of increased water abstraction upstream. This trend of eroding coastline is in common with many deltaic regions across the world, many of which are also responding to increased anthropogenic activities in their catchments (e.g. the Nile delta – White and El Asmar, 1999, and the Yellow River – Chu et al., 2006; Cui and Li, 2011).

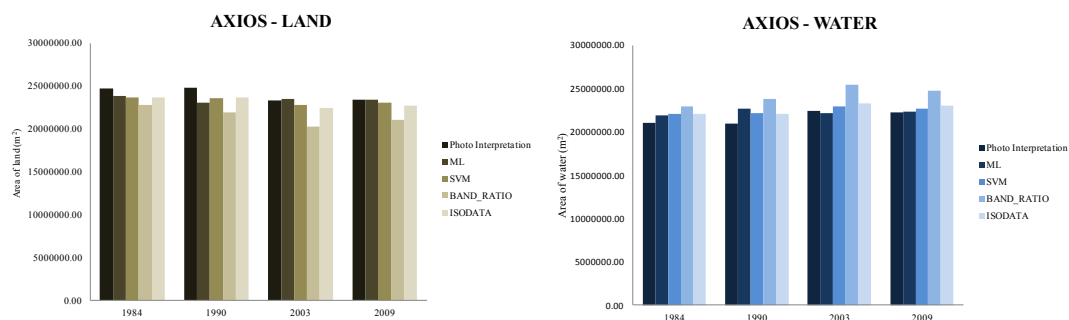


Figure 4 - Graphs showing the changes in the areas characterized as land and water between 1984 and 2009 for all methods used.

The evidence of net deposition during some periods is interesting in the context of the longer term trend of coastline erosion. Whether this deposition (e.g. in 2003-2009) indicates a decrease in the longer term trend of erosion, and whether or not these changes are due to changes in anthropogenic (e.g. agricultural intensification on floodplains causing an increase in sediment load) or climatic (e.g. changes in flood frequency and magnitude) remains to be seen, and will be explored elsewhere. What is evident from these data is that, overall, the surface area available for utilisation by human

activity has decreased. Concurrently, the surface area required by humans for settlement expansion and agricultural activity as a result of an increase in population has increased. Zalidis et al., (2007) showed that settlements had expanded by 27 % since 1994 and an expansion of 8 % in road area. Thus the pressure on land use, and thus on the ecological and geomorphological sustainability of this region has increased not just as a result of an expansion of human activity but as a result of the reduction in the available land surface. Dealing with the tensions which this conflict may cause will be a significant challenge for catchment managers in the future. Whether this level of urbanisation in the delta region has impacted on hydrological and sedimentological pathways and processes is a matter for further research. Interestingly, Zalidis et al., (2007) also found that the irrigated area was relatively stable between 1994 and 2004 and suggested that this showed that irrigation had reached capacity before 1994. However, 22 % of the irrigation had to change location. As well as being due to salinisation, drainage or EU policy reasons, this could indicate an increasing pressure on land caused by coastal erosion.

A preliminary analysis of the similarities and differences between the different image analysis techniques shows that for the most part, the SVM, Band Ratio and ISODATA methods correspond reasonably well to the photo interpretation method. However, different quantitative results were obtained between the methods in estimating the total erosion and deposition rates in the area. This can be attributed largely to the different operation and assumptions each technique. For example, ML as a parametric classifier requires the assumption of normally distributed classes over the area to be classifier, which might not always be the case in nature. Evidently, between all methods included in our study herein, SVMs provided the closest results to photo-interpretation (our reference dataset). This can be due to a number of reasons. SVMs offer additional benefits in contrast to alternative classification models, for example artificial neural networks (ANNs) or ML. SVMs have been designed to be able to identify an optimal separating hyperplane for classes' separation, which makes those classifiers resilient to getting trapped in local minima, as for example with ANNs. Also, their implementation does not require the assumption of statistical distribution of the data to be classified, as for example ML classifier. On the other, a key disadvantage of all classifiers applied herein is that those do not operate on a sub-pixel level. The latter can theoretically significantly reduce the accuracy of those classifiers especially when applied with coarse spatial resolution data, due to possible mixture problems occurred that result to misclassification errors.

Although the magnitude of erosion and deposition vary between methods, in general, these methods are in agreement as to whether the delta is experiencing net erosion or net deposition. The exception to this is in the period 1984-1990 where only the ISODATA method agreed with the photo interpretation in showing that net deposition was taking place, whereas the other three methods indicated erosion was taking place. With the exception of the period 1984-2009, the ML method disagreed with the photo interpretation method.

5. Conclusions

This study has utilised freely distributed high resolution remotely sensed data and GIS and different image processing techniques to demonstrate that the Axios River delta has experienced extensive erosion between 1984 and 2009. Although there are differences between each method for different time periods, all are in agreement that this hugely significant coastal region has degraded during the past ~ 25 years. This study has also shown that it is possible to use a wide variety of different methods of analysing remotely sensed data in order to obtain measurements of geomorphic processes at long decadal timescales and at large spatial scales. The differences in each method demonstrate, however, that more work is needed to validate estimates from such methods and that efforts should be made to integrate remotely sensed data with ground-based observations and topographic surveys where possible. These results may be used to inform future catchment management schemes in order to ensure the geomorphological, ecological and economical sustainability of the region.

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7. References

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