Alexandridis, T.K., Monachou, S., Skoulikaris, C., Kalopesa, E., and Zalidis, G.C., 2015. Investigation of the temporal relation of remotely sensed coastal water quality with GIS modeled upstream soil erosion. Hydrological Processes, 29: 2373-2384.

Investigation of the temporal relation of remotely sensed coastal water quality with GIS modeled upstream soil erosion

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Abstract

Hydrological processes at the river basin influence the quality of downstream water bodies by controlling the loads of nutrients and suspended solids. Although their monitoring is important for social, economic and environmental reasons, in-situ measurements are too expensive and thus too sparse to describe their relations. The aim of this study is to investigate the temporal relations of soil erosion in the upstream part of river basins with water quality characteristics in the downstream coastal zone, using satellite remote sensing and GIS modeling. Data from satellite missions of MODIS, SRTM and TRMM were used to describe the soil erosion factors of the Universal Soil Loss Equation in three river basins, and MERIS satellite data was used to estimate chlorophyll-*a* and total suspended matter concentrations in the coastal zone of northwest Aegean Sea in Greece, where the rivers discharge. The resulting time series showed an average correlation of upstream rainfall with downstream water quality, which increased when soil erosion was introduced. Higher correlations were observed with the use of a time lag, revealing a variable delay between the three test sites. Lower correlation coefficients were observed for chlorophyll-*a*, due to the sensitivity of algae to environmental conditions. The use of free of charge satellite data and easy to operate GIS models renders the findings of this work useful for coastal zone management bodies, in order to help increase aquaculture productivity, predict algal blooms, and predict siltation of ports.

Keywords: erosion, USLE, chlorophyll-*a*, TSM, remote sensing, GIS

1. Introduction

Upstream hydrological processes influence water quality at downstream parts of the basin (reservoirs, estuaries and coastal areas) through river discharges. Specifically for rain induced soil erosion, its major off-site effect is on water quality due to increased sediment and chemical concentration in suspended or dissolved forms (Lal, 1998). These include inorganic and organic sediments, agricultural nutrients and pesticides. High values of suspended sediment loads can affect aquatic organisms' respiration, feeding, reproduction and change the community structure (Lenat, 1984; Wood and Armitage, 1997; Linderfelt and Turner, 2001). High concentration of nutrients in coastal water bodies can lead to algal blooms, and presence of pesticides may impact the food chain with severe health and economic consequences (Nikolaidis *et al.*, 2005). This degradation of water quality may reduce the ability of water bodies to provide economic services, leading to lower revenues for the fishing, aquaculture, and tourism industries (Ribaudo and Young, 1989).

Measurement of soil erosion is a highly laborious procedure and is limited to a few experimental sites (Nearing *et al.*, 1999; Romero-Díaz *et al.*, 1999; Bagarello *et al.*, 2008). However, the severe economic and environmental impact of soil erosion has resulted in the development of several models for assessing soil loss due to sheet and rill erosion (Pimentel *et al.*, 1995). These are divided into physical models (e.g. PESERA - Pan-European Soil Erosion Risk Assessment), conceptual models (e.g. SWIM - Soil and Water Integrated Model) and empirical models (e.g. USLE - Universal Soil Loss Equation). Their implementation is based on easily measured parameters that describe the main factors of water induced soil erosion, such as rainfall, erodibility of the soil type, slope of the eroded location, and vegetation cover of the land (Wischmeier and Smith, 1978; Krysanova *et al.*, 1998; Kirkby *et al.*, 2008). More complicated models which integrate modules targeted on the simulation of hydrology and hydraulic processes have also been used to estimate soil erosion (e.g. WEPP - Water Erosion Prediction Project, EUROSEM - European Soil Erosion Model, AGNPS - Agricultural Nonpoint Source Pollution Model) and sediment trapping by dams, but the reliability of their outputs heavily relies on the accurate description of multiple parameters and on abundance of data (Nearing *et al.*, 1989; Morgan *et al.*, 1998; Tiwari *et al.*, 2000; Rode and Suhr, 2007; Lewis *et al.*, 2013).

Changes in water quality in coastal areas, as measured by chemical and biological parameters, display high temporal and spatial heterogeneity due to weather conditions, coastal morphology and water dynamics (Nezlin *et al.*, 2010; Navarro *et al.*, 2012). Because of the immense environmental, economical and health related impacts of coastal ecosystems' water quality, the latter should be regularly monitored using in-situ water sampling and analyses in the laboratory, or automated telemetric stations. However, in-situ measurements are infrequent and telemetric monitoring networks are usually sparse due to the associated high costs and lack of technological equipment. Thus, infrequent water sampling could lead to underestimation of the sediment load in streams (Gippel, 1995). Numerical modeling has been used to predict the water quality of various water bodies with varying success, mainly depending on availability of input data (Rode and Suhr, 2007). Satellite remote sensing has been used successfully for monitoring marine and coastal ecosystems, providing high levels of accuracy (Doerffer *et al.*, 1999; Nezlin *et al.*, 2010), and several, often dedicated, satellites have been used for this purpose, such as SeaWIFS, MODIS, MERIS and AVHRR. In a recent example, automated classification of MODIS satellite images have been used to map the extents of river plumes discharging in the vicinity of the Great Barrier Reef, and connect it with a dispersion model (Álvarez-Romero *et al.*, 2013). Remote sensing offers several advantages, such as the wall-to-wall coverage and frequent observations at low cost. However, it may be hindered by frequent cloud coverage during rainy periods, and only few water quality parameters can be monitored operationally, such as chlorophyll-*a* (Chl-*a*), total suspended solids (TSM) and sea surface temperature (SST), although several others are routinely monitored, such as coloured dissolved organic matter (CDOM) and euphotic depth (Schmugge *et al.*, 2002; Liu *et al.*, 2003).

In small scale river basins, various models have been introduced for the relational assessment of water quality to upstream hydrological processes (Ritchie *et al.*, 2003). A geographical information system (GIS) and 3D geographic analysis was used to link the accumulated sediment deposited in a reservoir over 64 years with the annual estimation of upstream soil erosion estimated by the Revised Universal Soil Loss Equation (RUSLE) (Chang *et al.*, 2003). Similarly, the AGNPS model coupled with a GIS was used to estimate sediment and total phosphorus yield from upstream soil erosion (Rode and Suhr, 2007). Suspended solids in stream discharge and sediment yield have been successfully connected to upstream precipitation and other factors contributing to soil erosion (Wilson *et al.*, 2001; Sammori *et al.*, 2004). Changes in river water quality have been studied in relation to upstream land cover pattern, taking into account the changing patterns of land use (Zhang *et al.*, 2013). For the case of rainfall and river ecosystems, both positive and negative relationships have been observed with water quality parameters, which implies that rainfall could have two roles, one flushing the sources of pollutants into the water body, the other mitigating the concentration of pollutants in the water body (Zhang *et al.*, 2013).

On larger scales, coloured detrital material has been connected to modeled river discharge (Chérubin *et al.*, 2008), and catchment precipitation has been connected to Chl-*a* and SST in river plumes (Nezlin and DiGiacomo, 2005; Warrick *et al.*, 2007; Lihan *et al.*, 2008). However, precipitation is not the only factor influencing river runoff, sediment transport and downstream water quality. The aim of this paper is the investigation of the temporal pattern of soil erosion in the upstream part of river basins in relation to water quality characteristics in the downstream coastal zone. The specific objectives are (i) the development of a time series of catchment related (rainfall, vegetation indices, soil erosion) and coastal water quality parameters (Chl-*a*, TSM) with emphasis on satellite remote sensing and GIS analysis, and (ii) the exploration of the parameters' correlations and time lag using time series analysis.

2. Materials and methods

2.1 Study area

The study area includes the Axios, Gallikos and Aliakmonas river basins and the Thermaikos Gulf in northwest Aegean Sea in Greece, where the rivers' outlet is located (Figure 1). The main characteristics of the river basins are described in Table 1 (Ganoulis and Zinke Environmental Consulting, 2004; Karageorgis *et al.*, 2005; Alexandridis *et al.*, 2006; Baltas, 2008).

Both the Axios and Aliakmonas rivers are dammed, with 19 large and over 100 small dams and 7 large and 2 small dams in their watershed, respectively. The average flow of the Axios river is estimated at 158 m^3 s^{-1}. Winter peak flows may exceed 500 m^3 s^{-1} while very low flows (less than 20 m^3 s^{-1}) frequently occur during dry summer periods (Karageorgis *et al.*, 2005). In the Aliakmonas river basin, approximately $294*10^6$ m^3 of the available water volume is diverted annually to the irrigation networks of the plain, while $64*10^6$ m^3 is used for the water supply of the city of Thessaloniki (population > 1M). According to the hydrological balance of the Gallikos River, evapotranspiration, infiltration and superficial runoff stand at 85.1%, 4.5% and 10.4%, respectively, indicating the routine drying up of the river during summer (Mattas and Soulios, 2011).

The deltas of the rivers form part of the Axios - Loudias - Aliakmonas Estuaries National Park, which is a large complex wetland system covering an area of approximately 320 km^2. Because of its great ecological importance, it has been designated as part of the European Natura 2000 Network and is listed in the Ramsar Convention on Wetlands of International Importance.

The Thermaikos Gulf is a relatively shallow gulf with a maximum depth not exceeding 70 m (Karageorgis *et al.*, 2003; Kombiadou and Krestenitis, 2011). The morphology of the seabed of the gulf (sandy-muddy substrate) and the fact that it is a mesotrophic gulf is the reason that the Thermaikos is one of the most important trawling sites in Greece (Zervakis *et al.*, 2005). Moreover, the local economy is strongly supported by aquacultures, which produce more than 30,000 t of mussels annually and constitutes 88% of the Greek production. The water circulation in the gulf is mainly wind induced and follows a counter-clockwise pattern: from the central and eastern part to the north and from the western part to the south (Poulos *et al.*, 2000). The anthropogenic pressures include the sewage of the city of Thessaloniki, the drainage of the agriculture and the effluence from the Axios and Aliakmonas rivers. The Gallikos River drains waste water from more than 250 industrial units before discharging intro the gulf. These inputs have rendered Thermaikos Gulf eutrophic, which is in contrast to the deep oligotrophic Aegean Sea (Nikolaidis *et al.*, 2006).

Four test sites (sized 3x3 km, containing 100 MERIS or 9 MODIS pixels each) were selected in the Thermaikos Gulf, strategically located to emphasize the expected variation in water quality parameters near the shallow waters at the estuaries of the three rivers (Axios, Aliakmonas, Gallikos), and the open water (Thermaikos). The average depth in the three rivers' test sites was 23m, and the open water test site was 65m.

2.2 Data used and methods

Modeling soil erosion with GIS

The Universal Soil Loss Equation (USLE) is the most widely used empirical model (Kinnell, 2010), which estimates the soil erosion risk A [t ha^{-1} $year^{-1}$] with the following equation:

$$A = R \times K \times LS \times C \times P$$

Where:

R is the rainfall intensity factor [MJ mm ha^{-1} h^{-1} $year^{-1}$], which was approximated using the Modified Fournier Index (Arnoldus, 1978): $MFI=\Sigma(pi^2 / p)$, where pi is the mean monthly rainfall (mm) and p is the mean annual rainfall (mm). TRMM (Tropical Rainfall Measuring Mission) data were used as input for R (Alexandridis *et al.*, 2013b). The 3B43 product providing mean monthly precipitation in mm h^{-1}, with accuracy higher than 0.5 mm h^{-1} and spatial resolution 25 km was utilized.

K is the soil erodibility factor [t ha h ha^{-1} MJ^{-1} mm^{-1}], which was calculated with data from the European Soil Database (Panagos, 2006) at a scale 1:1,000,000 (Van der Knijff *et al.*, 2000). A conversion table was used to estimate K factor according to the soil texture and organic matter content (Stone and Hiloborn, 2012). According to soil surveys of north Greece in the last decade, the organic matter content did not decrease (Misopolinos *et al.*, 2010; Misopolinos *et al.*, 2014).

LS is the topographic factor [unitless], which accounts for the influence of slope steepness and slope length on soil erosion. This was calculated from the equation described in Moore and Burch (1986): $LS = (A_f D / 22.13)^{0.4} (\sin\beta / 0.0896)^{1.3}$, where A_f is the flow accumulation (pixels), D is the pixel size (m), and β is the slope angle. A digital elevation model from SRTM (Shuttle Radar Topography Mission) data at 90 m spatial resolution was used to estimate the flow accumulation and slope (Vrščaj *et al.*, 2007).

C is the vegetation cover factor [unitless], and is defined as the ratio of soil loss under the given vegetation cover to that which would occur under continuously bare soil. It was calculated from the equation C = exp (-a (NDVI / (b - NDVI))), where a and b are constants derived from a similar work in Italy (Van der Knijff *et al.*, 1999), and NDVI is the Normalized Difference Vegetation Index (Rouse and Haas, 1973). It was calculated using data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on board the Terra satellite. The product MOD13Q1 was used, which is available every 16 days with a spatial resolution 250 m.

P factor [unitless] refers to the measures taken at each site to reduce the risk of erosion. Due to a lack of data in the study area, the specific factor was assumed to be equal to 1.

No experimental data were available for validating the accuracy of the resulting soil erosion risk maps, but the latter were comparable with results obtained in adjacent river basins (Panagos *et al.*, 2011; Alexandridis *et al.*, 2013b).

Monitoring water quality parameters with remote sensing

The MERIS (Medium Resolution Imaging Spectrometer) sensor on board the ENVISAT satellite (2002-2012) was mainly designed for ocean and coastal water remote sensing (Doerffer and Schiller, 2007). The satellite images (FRS_1P at 300 m) were acquired every 8 days, depending on weather conditions, and were used for the estimation of water quality parameters (Chl-*a* and TSM). The Case-2 Regional Processor Algorithm for coastal waters (C2R) was used in the BEAM software (Toolbox for analysis and processing of EO data, Version 4.8) to estimate the concentrations of Chl-*a* and TSM in Case II regions (Doerffer and Schiller, 2007). The C2R algorithm consists of atmospheric correction and bio-optical procedures, and uses neural networks to compute the water quality parameters which absorb and scatter light in the visible spectrum.

The resulting maps were validated using in-situ collected water samples and analyzed in the laboratory, revealing a mean paired difference of 1.37 mg m^{-3} for Chl-*a* (N=22, p=0.2289) (Monachou *et al.*, 2014). Lack of appropriate TSM measurements prevented its validation in the test site, but the same combination of data, tools and team has produced very good results in the coastal zone of northwest Black Sea, with an average difference of 5.02 g m^{-3} (RMSE=26%) from 120 observations (Alexandridis *et al.*, 2013a).

Statistical analyses

The above mentioned data were collected for two sequential years from July 2009 to June 2011, with the datasets having a variable time step.

The time series analysis required common temporal reference, thus temporal interpolation using the spline method (Spath, 1995) was implemented to establish a common step of 8 days. The spline function's lambda (smoothing parameter) was selected so that the interpolated data described no less than 90% of the variability of the input data.

The time series of water quality parameters were normalized in order to eliminate the seasonal variation with the subtraction from the time series of Chl-*a* and TSM of each test site, the equivalent value of the Thermaikos test site. The Thermaikos test site had been selected in the open sea, away from river plumes, thus the variation of its parameters was attributed mainly to the seasonal effect of environmental conditions.

In a similar manner, Nezlin and Li (2003) had removed the climatological cycle from their time series using a sine function.

The relations between the examined parameters were investigated through correlation analysis. Moreover, time lag correlation analysis was used to examine delays in the effect of parameters. Cross correlation analysis is usually applied in signal processing when trying to find patterns in the different signals examined. To do this, the base signal is superimposed to the test signal at increasing time delays (lags) throughout the time continuum.

3. Results and discussion

3.1 Time series of rainfall and soil erosion

No major differences among the cumulative precipitation of the three river basins were observed (Figure 2). Local maxima appear during autumn and spring months, with an exceptional maximum in January 2010. In contrast, minima occur during dry summer months. All observations are in accordance with the description of the Mediterranean climate (Bolle, 2003; Lionello *et al.*, 2006). The spatial distribution of rainfall is quite homogeneous, with slightly higher values in the upstream mountainous parts of the river basins (Figure 3). This homogeneity could be due to the low spatial resolution of the TRMM data, but mostly due to the geographical location of the river basins at the western side of the Pindos mountain range, which is within a single biogeographical zone (http://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-1).

The soil erosion between the three river basins displays wide seasonal fluctuations, while Aliakmonas River has consistently higher values than Axios, which in turn is always higher than Gallikos (Figure 4). The terrain's slope is the main reason behind this stratification, with Gallikos River having the lowest slopes (Figure 1). The graphs of soil erosion and precipitation do not have the same pattern since erosion is significantly affected by vegetation cover. The peaks during the winter period and the troughs during summer are due to the combined effect of rainfall and vegetation coverage. The second, higher peak of January 2010 is due to the unusually high rainfall. The spatial distribution of soil erosion follows the detailed pattern of vegetation cover and slope. Higher values appear in the mountainous upstream areas, and no erosion in the flat downstream floodplains (Figure 5). The straight horizontal line to the south of Aliakmonas basin is due to a drastic increase in rainfall across the large pixels of TRMM.

3.2 Time series of Chl-*a* and TSM

Having removed the seasonal influence from the time series after normalization, the Chl-*a* concentration presented a highly undulating pattern (Figure 6). The trend for an increase from July 2009 to April 2010 was followed by a drop in all test sites, while the trend showing an increase from July 2010 was interrupted by drastic drops in January and April 2011. Despite the observed fluctuations, it is clear that Axios site has consistently higher values of Chl-*a* than that of the Aliakmonas, which in turn has higher values than the Gallikos.

The temporal pattern of TSM showed the lowest values during the summer months (Figure 7). All sites followed a similar pattern, with the Aliakmonas site being highly variable during 2009-2010. During the first evaluation year, TSM values were significantly higher than 2010-2011 (mean samples difference=0.8465 g m^{-3}, N=95, p=0.0015). The comparison among the test sites revealed a higher concentration of TSM in the Axios site, with exception of some extreme peaks in the Aliakmonas site. It is noteworthy that the Aliakmonas river basin has higher overall soil erosion risk, while Axios test site shows higher concentrations of TSM. The operation rules and schedule of the multiple dams on each river basin is probably the cause of these inconsistencies.

The spatial distribution of Chl-*a* and TSM demonstrated an increased concentration of the two parameters in the western part of the Thermaikos Gulf, influenced by the shape and size of the rivers' plumes, which in turn are governed by the prevailing wind (Figures 8 and 9). On the southern and eastern part of the gulf, the parameters' concentration was considerably lower throughout the time series of maps.

3.3 Relation of upstream hydrological processes with downstream water quality

The results of the correlations between the mean precipitation in the upstream part of the basins and the water quality parameters at the test sites are presented in Table 2. Positive but rather low correlations were noticed, with the correlation coefficient (r) ranging from 0.21 to 0.42. Higher correlations were noted between precipitation and TSM, indicating that the concentration of suspended matter is more sensitive to the amount of water outflow from the river mouth, rather than Chl-*a* which is also influenced by the composition of suspended matter, the concentration of nutrients and other environmental parameters such as temperature (Nezlin and Li, 2003). An exception to the above is the TSM concentration at the Gallikos test site where there is no correlation with precipitation. The time lag correlation analysis demonstrated an increased level of correlation, especially for the TSM where a higher positive correlation ($r > 0.5$) was observed. All time lags of maximum correlation coefficient (r_{max}) for Axios and Aliakmonas range from 24-29 days, which indicates that the water quality parameters are closely related and influenced similarly by the precipitation upstream. The time of r_{max} for Gallikos River is below 8 days, due to its basin characteristics (Table 1).

Using the mean soil erosion (A) in the river basin as the independent variable in the correlation with the water quality parameters at the test sites (Table 3) demonstrated a general increase in the correlation coefficients, as compared to the ones for precipitation. An exception is the Chl-*a* of the Aliakmonas and Gallikos sites where no increase is noted. A similar increase is observed in the lagged correlations, where r_{max} reaches high positive values (up to 0.79). In parallel, the time lag of r_{max} ranges from 19 to 36 days. This is an indication that upstream eroded material drives the concentration of TSM downstream, as well as the development of photosynthesizing algae with a certain delay, both of which influence the water quality of the collector water body. Similar to the previous results with precipitation, the Gallikos site shows no apparent delay in the r_{max}.

3.4 Discussion

In this study, emphasis is given to the investigation of temporal relations between upstream hydrological processes (rainfall and soil erosion) to water quality parameters (Chl-*a* and TSM) on a downstream water body (coastal zone). Similar relations regarding the rainfall have successfully been identified in the past (Nezlin and DiGiacomo, 2005; Baek *et al.*, 2009; Zhou *et al.*, 2011), nevertheless the soil erosion influence which is initiated in this research work has never been assessed. The results demonstrated an increased correlation for soil erosion than for precipitation. This is because the outflow of organic and inorganic materials that influence water quality is governed by other factors other than rainfall, which are already included in the soil erosion estimates through the USLE. However, the close similarity of the result between rainfall and soil erosion suggests that rainfall is one of the most important upstream factors that influence downstream water quality characteristics, as it is confirmed by the univariate sensitivity analysis of USLE where soil erodibility, hydraulic conductivity and rainfall intensity are indicated as the most influential parameters (Morgan and Nearing, 2011).

The identified medium level of correlations between upstream catchment processes and downstream water quality parameters can be justified by the following arguments. First, not all eroded material is transported to the river outflow, since this process is also influenced by a number of natural factors, and the sediment delivery ratio (SDR) is commonly used in erosion and sediment transport studies (Walling, 1983). Second, human interventions in the rivers' courses influence the water flow and the sediment transport, such as dams, artificial lakes, irrigation works, reservoirs and channelization of river courses. In the Axios River, the mean annual suspended solid discharges from historical data (70s) had been estimated at 1-2*10^6 t $year^{-1}$, whereas in the year 2000 estimates had been found 10 to 20-fold lower (0.1*10^6 t $year^{-1}$) (Karageorgis *et al.*, 2003). This significant reduction is related to the decrease of water discharge, as well as the construction of dams in the upper part of the basin. Large scale reduction has also been observed at 3 different dammed river basins in the south of France, where upstream of the dams, the TSM flood concentrations were always >100 mg L^{-1} and could reach 500 mg L^{-1}, while downstream from the dams, TSM concentrations rarely exceeded 10 mg L^{-1}, even during flood periods (Maneux *et al.*, 2001). High correlations had been noted between plume size and precipitation in Santa Monica streams, where higher slopes, smaller watersheds, excessive soil sealing and channelization of river beds had facilitated the fast outflow of most of the rain water (Nezlin and DiGiacomo, 2005). Finally, resuspension of sediment due to wind and currents could lower the correlations. However, this effect is negligible as compared to the sediment discharged by the river plumes of the study area (Violintzis *et al.*, 2009).

Higher correlations were noted between upstream catchment remotely sensed observations and TSM rather than with Chl-*a*. This is an indication that the concentration of suspended matter is more sensitive to the amount of water outflow from the river mouth, rather than Chl-*a* which is influenced also by the composition of suspended matter, the concentration of nutrients, the photosynthetically active radiation (PAR), other environmental parameters and meteorological conditions (Paerl *et al.*, 1999; Baek *et al.*, 2009; Tello and Rodriguez-Benito, 2009; Rochelle-Newall *et al.*, 2011). This is supported by a high resolution oceanographic investigation of the East China Sea before and after the first filling phase (June 2003) of the Three-Gorges Dam (Gong *et al.*, 2006). This research indicated relatively high concentrations of Chl-*a* though the size of the Chl-*a* rich region had admittedly decreased. On the other hand, sediment loading was significantly reduced (by about 55%).

The highest correlations between upstream catchment hydrological processes and downstream water quality were noted with a delay of 20-36 days. This is longer than other reported lags, which refer however, to channelized streams of small catchments (Nezlin and DiGiacomo, 2005). Shorter lags have also been reported between rainfall and associated runoff or flood events using observations or numerical model simulations at various scales (Jothityangkoon and Sivapalan, 2001; Nicótina *et al.*, 2008; Mul *et al.*, 2009). The time lag was similar for the two large catchments (rivers Axios and Aliakmon), and for both Chl-*a* and TSM parameters. The fact that Chl-*a* and TSM have similar temporal behaviour suggests that the composition of suspended matter at these two test sites is mostly organic, rather than inorganic. Another reason for the variable correlations and time lags between the studied parameters is the source of nutrients. Surplus agrichemicals carried by runoff is readily bioavailable for algal nutrition, thus increasing Chl-a concentration but not TSM. On the other hand, eroded material increases TSM, but requires some time to release nutrients through mineralization.

Precipitation and soil erosion in the Gallikos river basin have no correlation with TSM at its mouth, because of the small size of the basin and the very smooth slopes. Moreover, suspended material are deposited in the river's estuary which is blocked by a dyke. Visual inspection of the time series of MERIS images has confirmed that no plume is formed at its mouth. This has been confirmed by Simeonov *et al.* (2003) who had reported a flow rate of less than 10 m^3 s^{-1} at the upper part of the river basin, which periodically drops to zero in the lower part. However, a correlation similar to the other rivers was noted for Chl-*a*, which may be explained by the appearance of nutrients slowly exiting the estuary, or the influence of the effluents of the nearby city of Thessaloniki.

The non use of dedicated catchment models which integrate analysis modules for the assessment of sedimentation and soil erosion as well as of water quality can be summarized by the two following reasons. First, the accuracy of the models' response highly depend on a-priori rigorous and purposeful parameterization in order to get as few “free” parameters as possible for which assessments through calibration are required (Refsgaard, 1997). In the investigated river basins, the almost complete lack of hydrological data such as stream-flow observations, was a deterrent factor for following a watershed basin modeling approach, as models' parameters calibration and optimization would be governed by uncertainty. The second reason is based on the heterogeneous nature of the basins and the difficulty of assembling non common variables. The Axios is a transboundary river basin where hydrologic information for the non Greek part of the basin is mostly inaccessible, while the Aliakmonas is a heavily modified river due to the large number of dams and reservoirs en cascade. For the latter, hydropower modeling should have been integrated with catchment hydrology modeling (Skoulikaris *et al.*, 2011), an issue which was out of the scope of the specific research.

Remotely sensed observations have been used in this study to estimate precipitation, vegetation cover, Chl-*a* and TSM, as it provides additional spatial information not present to in-situ data and hydro-dynamical and water quality models (Dekker *et al.*, 2001), and the reported accuracies are acceptable for operational use in various environments (Ouillon *et al.*, 1997; Doerffer and Schiller, 2007; Ouillon *et al.*, 2008; Doxaran *et al.*, 2012; Alexandridis *et al.*, 2013a; Monachou *et al.*, 2014). Case II is a globally applicable algorithm with sufficient validation, however local deviations are expected. A quantitative review of the accuracy of various remote sensing algorithms reveals that the Case II is successful at low to intermediate concentrations of Chl-a and TSM over a wide spatiotemporal range, while other algorithms show limitations, especially in Chl-a estimation (Odermatt *et al.*, 2012). In a more recent work in northern Baltic Sea, the Case II algorithm estimated successfully TSM but underperformed for Chl-a, by overestimating low concentrations and underestimated high concentrations (Attila *et al.*, 2013). Thus, correction coefficients were reported as a measure for local improvement (Attila *et al.*, 2013). Therefore, the global algorithms of remote sensing for Chl-a and TSM are advantageous, however specific improvements could provide higher local accuracies. In the Mediterranean region the TRMM products illustrate a misestimating of overall precipitation (Gabella *et al.*, 2008), with weak rain to be overestimated and intense precipitation to be underestimated (Lagouvardos and Kotroni, 2007). However, Feidas (2010) demonstrated that the 3B43 product, which is used in this research, provides increased correlation with gauge measurements for the Greek territory, with the bias to be estimated at 8.1% and the RMSE at 47.8%. The spatial resolution of remotely sensed datasets may seem low (as low as 300 m for water quality and 25 km for precipitation), however is much better in cases where limited data are available. Moreover, remote sensing data offer wall-to-wall coverage of observation, which minimized uncertainties. Datasets with a wide range of spatial distributions have been used together for modeling soil erosion risk (Alexandridis *et al.*, 2013b). The influence of the variable scales has been minimized as the results were eventually aggregated within river basins. Regarding the temporal resolution of the input data, it is similar to the weekly observations suggested for monitoring the water quality of the southern Frisial lakes (The Netherlands) with satellite images (Dekker *et al.*, 2001). More frequent observations of precipitation would have been smoothed by the large river basins and the water regulating constructions (dams, irrigation works, etc.). Also, accumulated rainwater over several days (even weeks) rather than daily observations has been suggested for plume studies and is recommended for coastal management (Nezlin and DiGiacomo, 2005).

4. Conclusions

This work has investigated the temporal relationship between upstream rainfall and soil erosion processes with water quality parameters (Chl-*a* and TSM) on a downstream water body (coastal zone).

Although the relations between upstream and downstream parameters were rather low, they were ameliorated with the use of soil erosion estimates. Moreover, there was an increase in the relations when a time lag was inserted. The time lag was similar for the two large catchments and for both water quality parameters, but lower for the smaller river basin.

Emphasis was given to the use of free-of-charge satellite remote sensing data, and easy to operate GIS models. Therefore, the findings of this work can be used in the workflow of the coastal zone management bodies, in order to help increase aquaculture productivity, issue warnings for algal blooms, and predict siltation of ports.

Acknowledgements

ENVISAT MERIS images were provided by the European Space Agency (ESA), and Terra MODIS images by the United States Geological Survey (USGS). The authors are thankful to the reviewers for their constructive comments.

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Tables

Table 1: Characteristics of the terrestrial part of the study area

River	River length (km)	Catchment area (km^2)	Mean altitude (m)	Annual precipitation (mm)	Annual discharge ($x10^6$ m^3)
Axios	388	24437	1124	707 (Bulgaria) 450 (Greece)	5000
Aliakmonas	290	6016	1020	640	2030
Gallikos	65	930	357	480	22

Table 2: Correlations and maximum correlation coefficients after time lag of precipitation (p) with water quality parameters

Dependent variable	Independent variable	Correlation coefficient (r)	Maximum correlation coefficient after time lag (r_{max})	Time lag of r_{max} (days)
Chl-*a* Axios	p Axios	0.234	0.359	27
Chl-a Aliakmonas	p Aliakmonas	0.215	0.403	26
Chl-*a* Gallikos	p Gallikos	0.302	0.302	<8
TSM Axios	p Axios	0.423	0.531	23
TSM Aliakmonas	p Aliakmonas	0.363	0.602	29
TSM Gallikos	p Gallikos	0.046	0.046	<8

Table 3: Correlations and maximum correlation coefficients after time lag of soil erosion (A) with water quality parameters

Dependent variable	Independent variable	Correlation coefficient (r)	Maximum correlation coefficient after time lag (r_{max})	Time lag of r_{max} (days)
Chl-*a* Axios	A Axios	0.311	0.360	19
Chl-a Aliakmonas	A Aliakmonas	0.210	0.386	25
Chl-*a* Gallikos	A Gallikos	0.303	0.314	8
TSM Axios	A Axios	0.551	0.791	35
TSM Aliakmonas	A Aliakmonas	0.426	0.658	29
TSM Gallikos	A Gallikos	-0.079	-0.079	<8

Figures

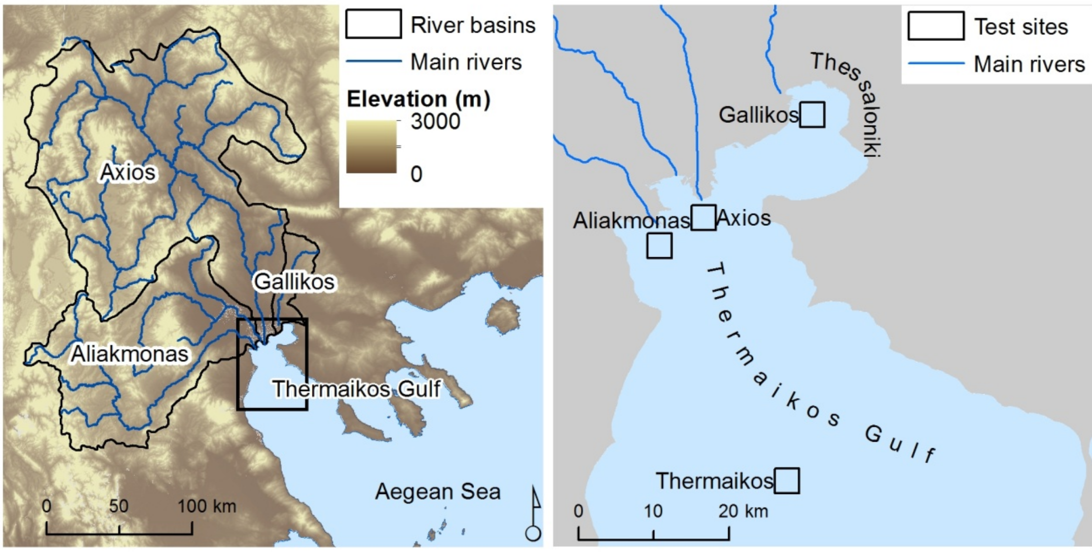

Figure 1: Location of study area, river basins and test sites.

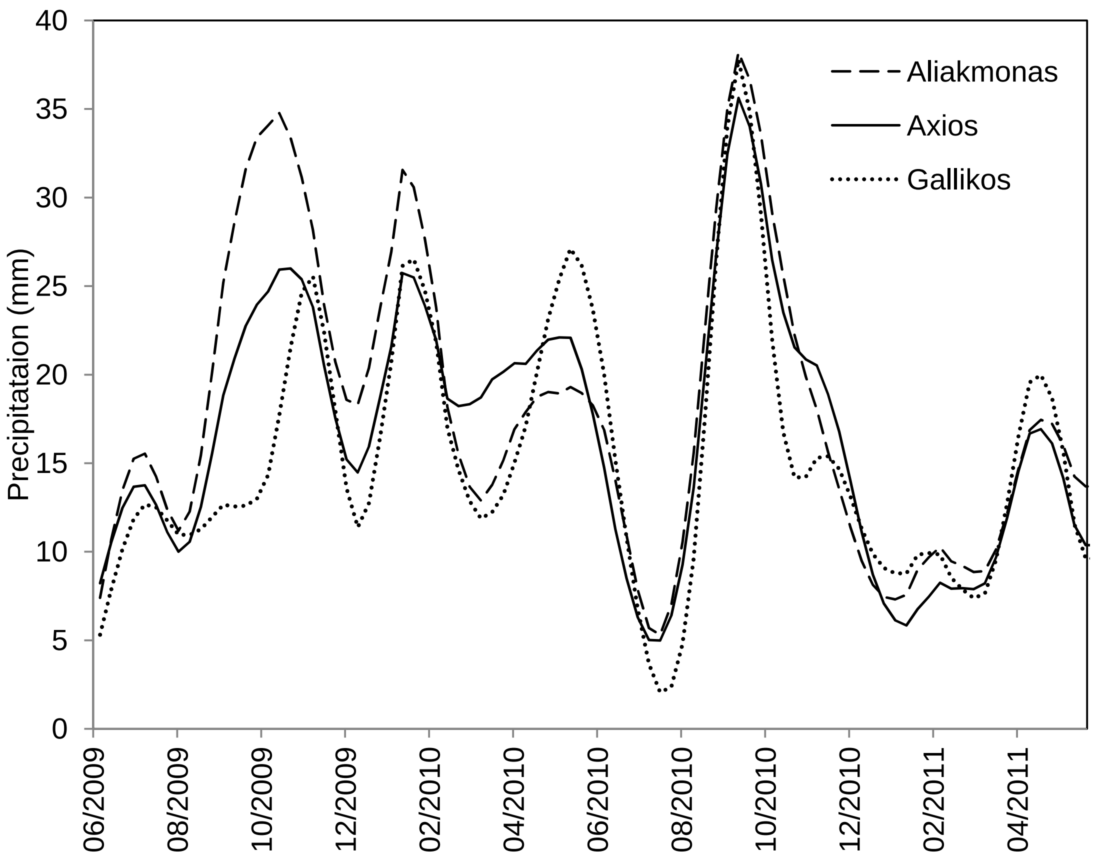

Figure 2: Mean rainfall per 8 days in the three river basins.

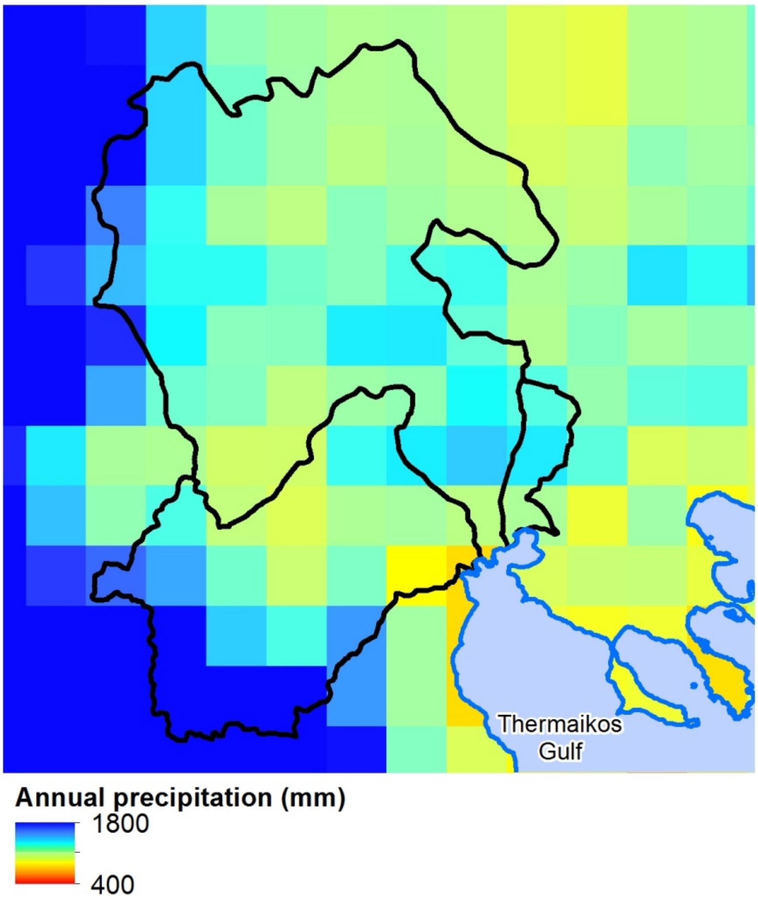

Figure 3: Spatial distribution of annual rainfall for the hydrological year of 2009-2010.

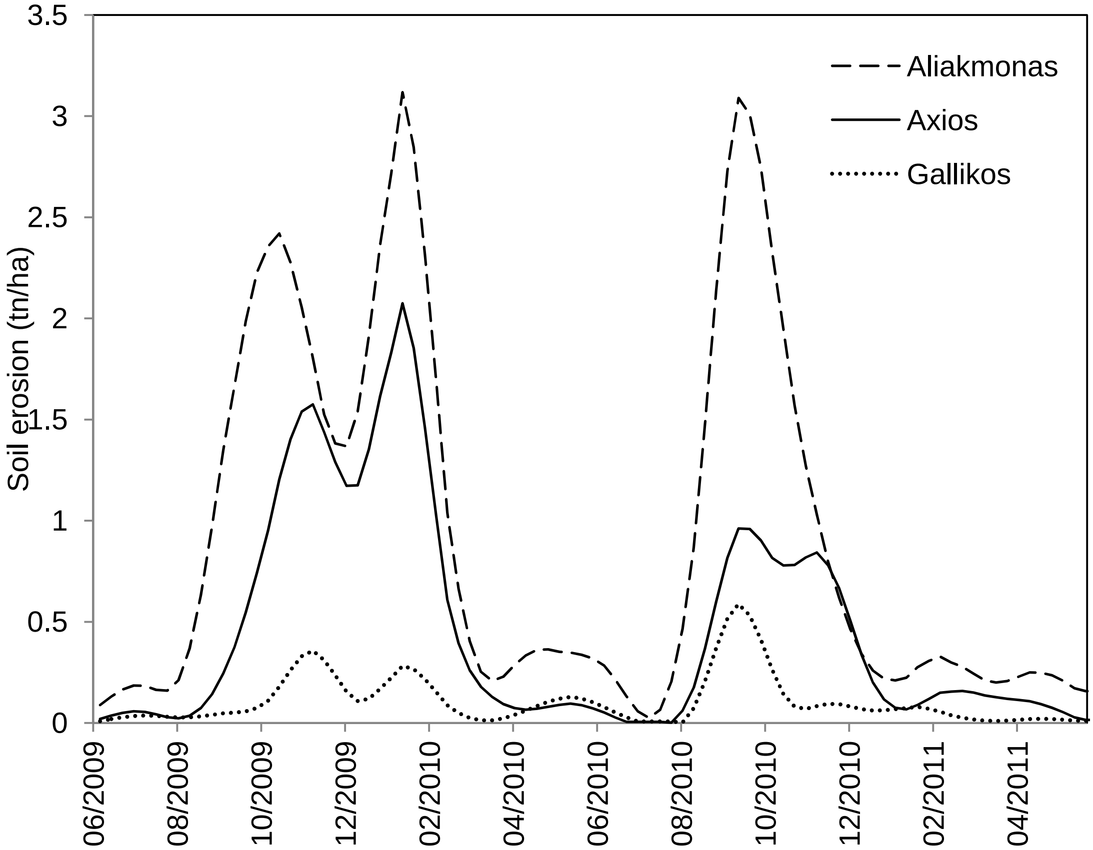

Figure 4: Mean soil erosion per 8 days in the three river basins.

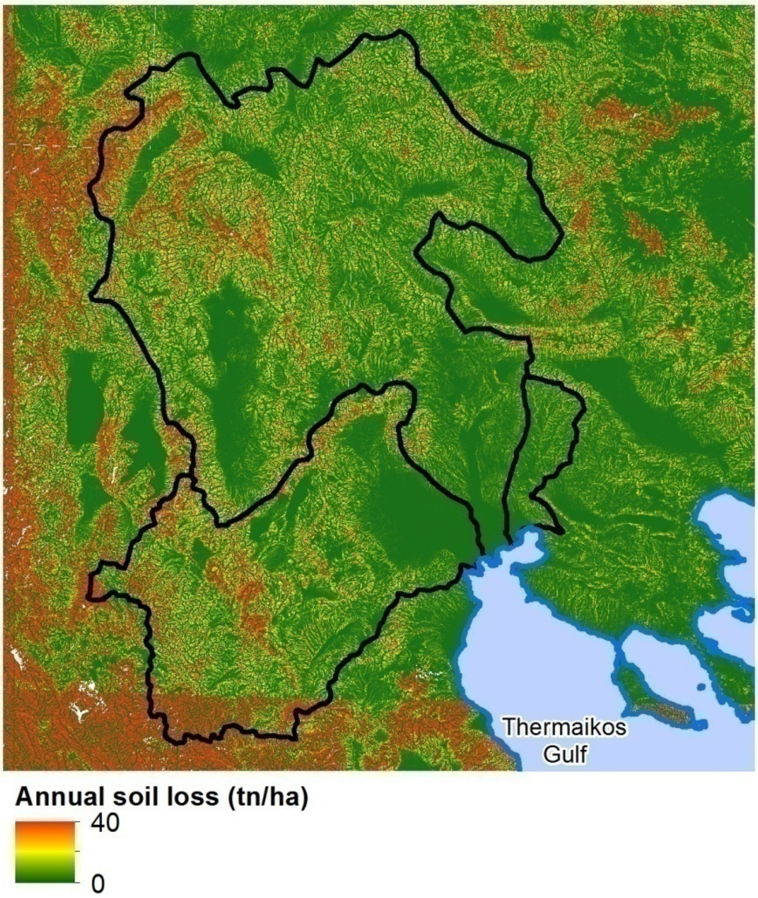

Figure 5: Spatial distribution of annual soil erosion risk for the hydrological year of 2009-2010.

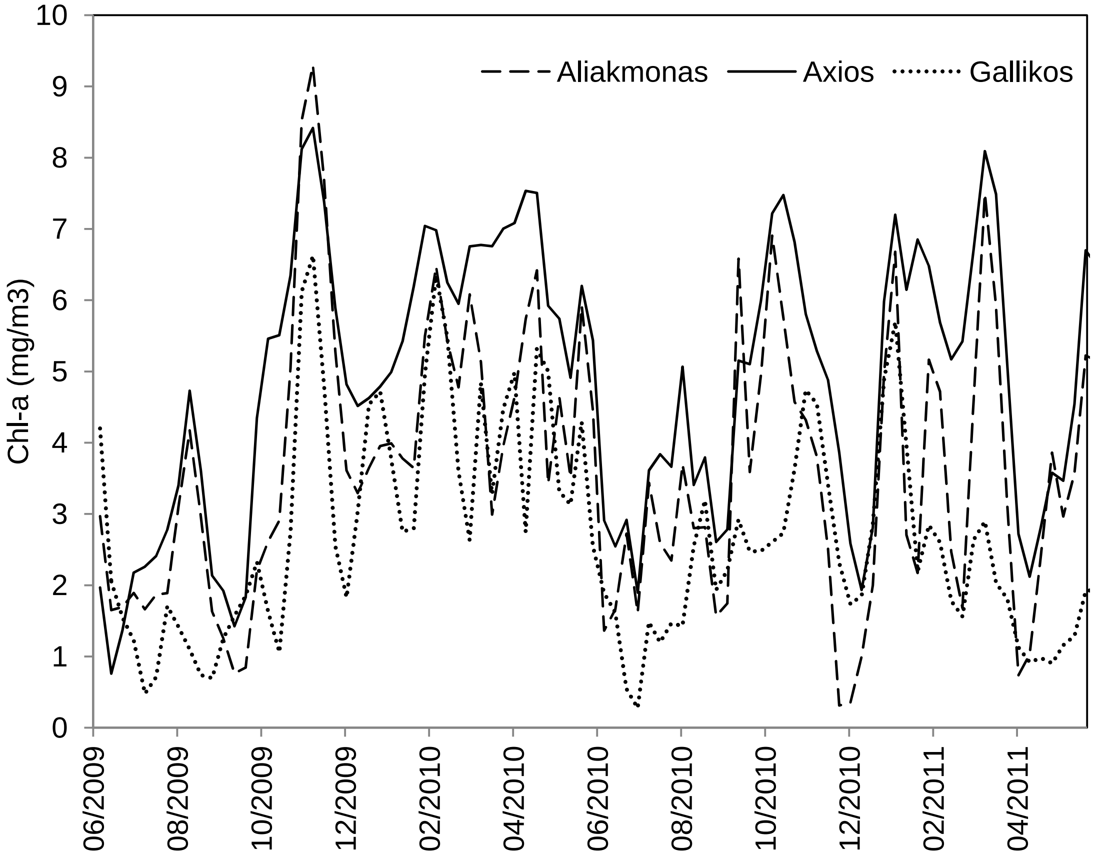

Figure 6: Normalized Chl-a concentration in the three test sites.

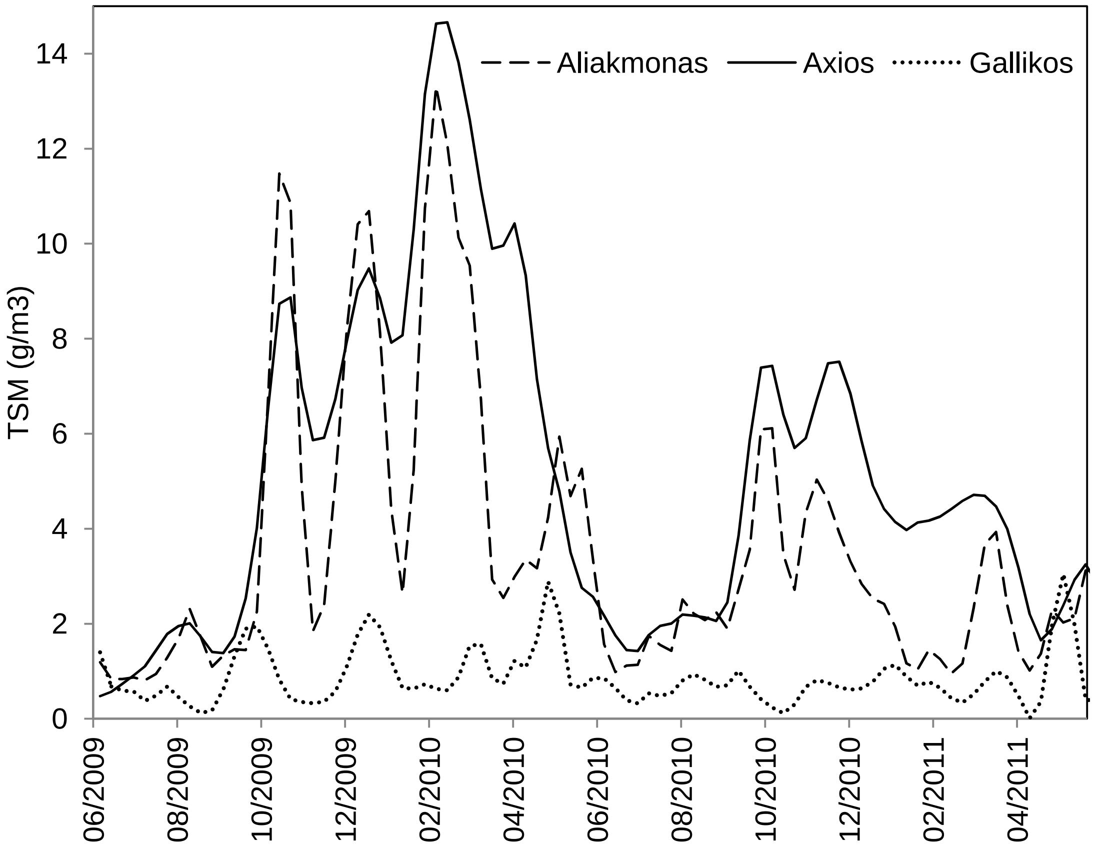

Figure 7: Normalized TSM concentration in the three test sites.

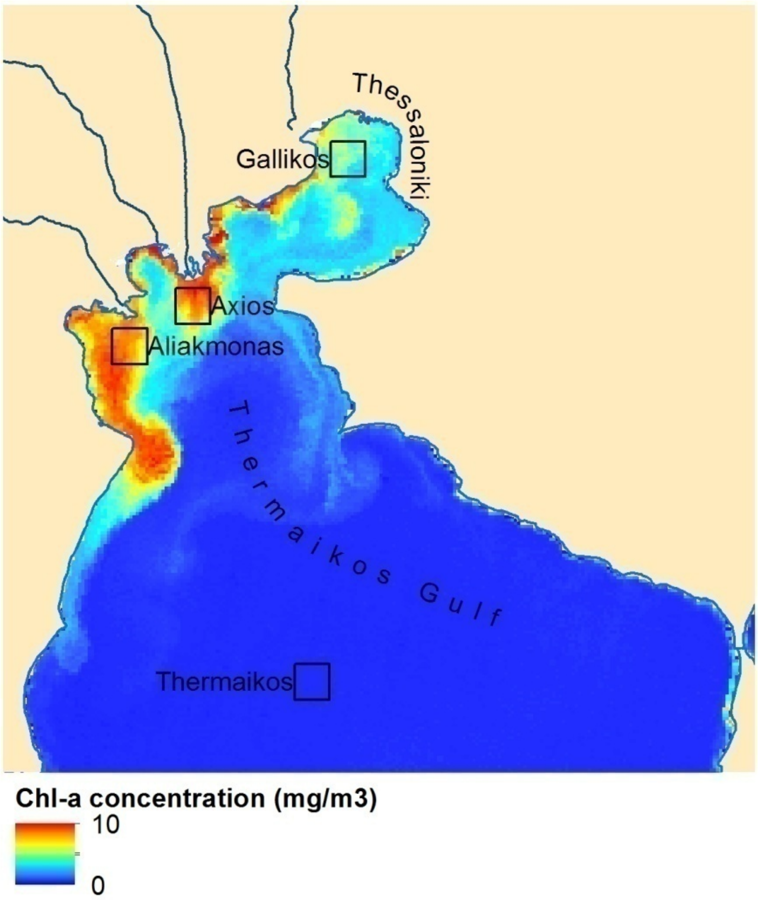

Figure 8: Spatial distribution of Chlorophyll-*a* (Chl-*a*) concentration on 30/09/2010.

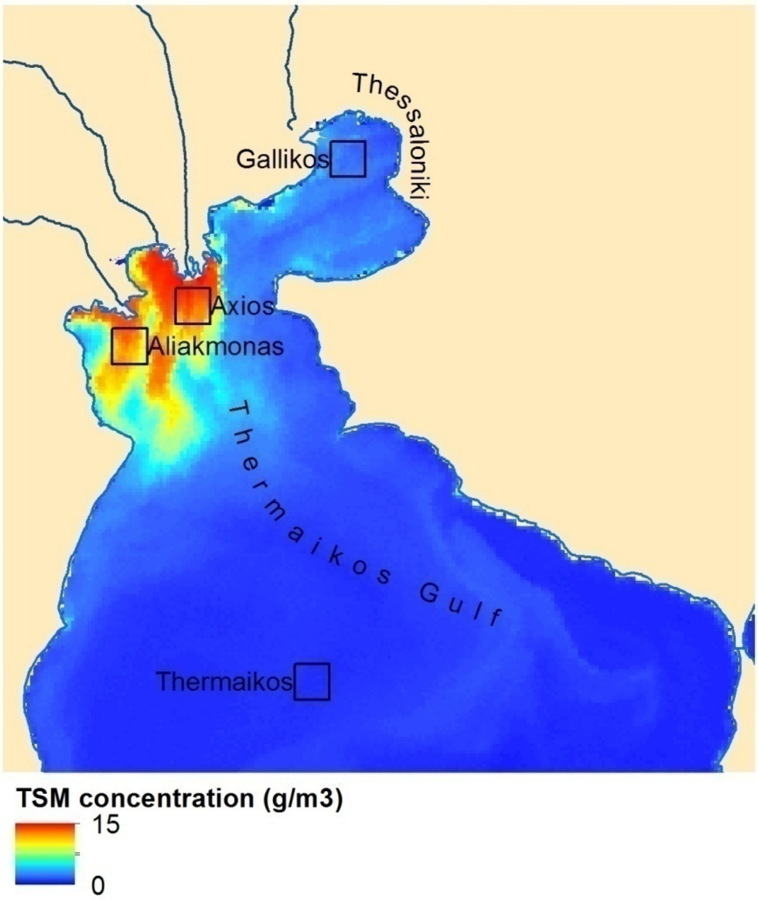

Figure 9: Spatial distribution of total suspended matter (TSM) concentration on 22/03/2010.