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To cite this article: Antonino Maltese, Fulvio Capodici, Giuseppe Ciralo & Goffredo La Loggia (2013) Coastal zone water quality: calibration of a water-turbidity equation for MODIS data, European Journal of Remote Sensing, 46:1, 333-347, DOI: [10.5721/EuJRS20134619](https://doi.org/10.5721/EuJRS20134619)

To link to this article: <https://doi.org/10.5721/EuJRS20134619>



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Published online: 17 Feb 2017.



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Coastal zone water quality: calibration of a water-turbidity equation for MODIS data

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Abstract

A nephelometric turbidity algorithm has been specifically calibrated for coastal waters in Sicily. To this purpose, intensive field campaigns were performed in July, August and September 2008. Measurements were collected *in situ* in three different gulfs. Statistical analysis suggests that field data should be spatially grouped but temporally separated; hence, new calibration parameters have been proposed.

Turbidity retrieved by applying the algorithm using literature coefficients and the ones calibrated *in situ* are shown and compared. The comparison demonstrated that a specific calibration was necessary for quantitatively monitoring turbidity in Sicilian gulfs.

Keywords: Nephelometric turbidity, algorithm calibration, MODIS images.

Introduction

Rivers bring to their mouths sediments following a seasonal behaviour and, occasionally, during floods [Doxaran et al., 2006]; once in the sea, sediments are dispersed by currents, then they settle and possibly are re-suspended by wave and currents energy, varying sea turbidity remarkably in the tidal zone [Cloern et al., 1989; Uncles et al., 2002; Wolanski and Spagnol, 2003]. Besides, human activities such as dredging influence turbidity magnitude locally and occasionally [Schoellhamer, 1996]. Consequently, water turbidity shows a wide range of variability both spatially and temporally [Maltese et al., 2011].

Turbidity is a measure of water transparency reduction due to suspended solids, organic matter particles and algal cells. It can be considered a quality parameter of sea coastal water, since it influences light penetration, planktonic and benthonic algae productivity [Cloern, 1987; Cole and Cloern, 1987; Pennock and Sharp, 1994; Fisher et al., 1999] as well as the growth of submerged vegetation and coral barriers [Moore et al., 1997; Anthony et al., 2004].

An increase in water turbidity strongly affects water warming due to the heat absorption by surface particles. The warming process determines a decreasing of dissolved oxygen concentration. Furthermore light is the most important element for photosynthetic processes

and a reduction in light intensity affects the life of aquatic plants and, then, further reduces dissolved oxygen.

Furthermore, spatial distribution of turbidity aids to understand the variability of Total Suspended Solids (TSSs) and, indirectly, coastal erosion as well as pollutant transport processes [Heyes et al., 2004].

The characterization of *in situ* turbidity can be carried out through an optoelectronic instrument. The working principle is based on the interaction between ray light and substances within water having different refraction index and absorbing part of the energy. These instruments are relatively not expensive and widespread during the last decade; nevertheless, conventional methods do not allow the characterization of turbidity dynamic due to spatial and temporal limits of field acquisitions. Remote sensors onboard of satellite platforms could be a valuable tool to retrieve repeated and synoptic maps of surface water turbidity. Limits to an operational use include the availability of clear images characterized by high temporal and spatial resolution [Stumpf and Pennock, 1989; Doxaran et al., 2002; Ruddick et al., 2003; Miller et al., 2005].

Several authors reported to successfully use satellite images such as Landsat TM [Curran and Novo, 1988; Harrington et al., 1989; Reddy and Srinivasulu, 1994].

A relationship commonly applied for sea coastal water has been given by Chen et al. [2007]: it has been calibrated using *in situ* observations (43 samples) acquired in Tampa Bay (Florida) between May 2003 and April 2006 and MODIS (MODerate-resolution Imaging Spectroradiometer) images.

Study objective

The research points towards the calibration of a nephelometric turbidity algorithm to be applied in coastal areas of the Mediterranean Sea.

The comparison between remote sensing estimation of water turbidity using Chen et al. [2007] retrieval algorithm and *in situ* data has shown the inadequacy to fit local field measures, as it will be shown within the results section of this paper.

The calibration dealt with a dataset characterizing three Sicilian gulfs; these are different in terms of morphology, bottom coverage and depth (shallow, medium and deep waters).

The case study of our research tested the newly calibrated relationship in order to evaluate water turbidity of some coastal marine waters in Sicily. The analysis of a long time series of the above mentioned parameter within three sub-zones of the Island coastal area is the specific goal of this paper, as well as to assess their statistical significance.

Study area

Data acquired in three main Sicilian gulfs (Castellammare, Augusta and Gela gulfs) have been used to calibrate the *NT* empirical relationship. These areas have been studied for many years owing to their peculiar characteristics (Fig. 1, right panel, white rectangles). Two zones having medium and high anthropic pollution pressures have been selected (Gela and Augusta gulfs), while the latter (Castellammare gulf) should be characterized by lower pollution.

Within these areas, data sampling has been carried out in three periods: at the beginning of July, August and September 2008.

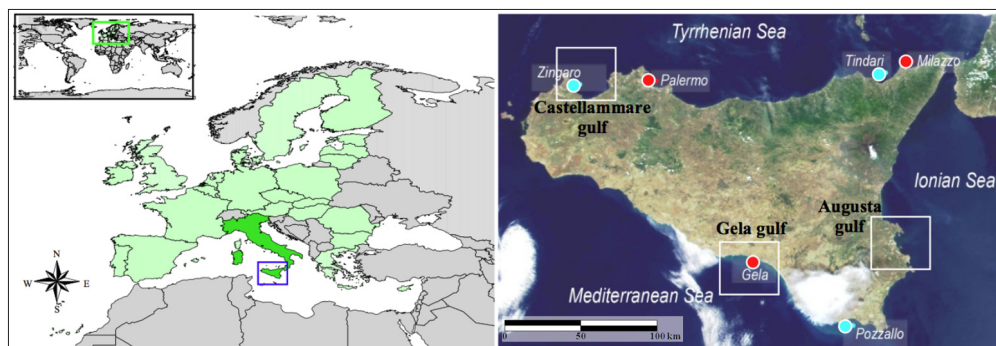


Figure 1 - On the left panel: Sicily Island is highlighted with a blue rectangle. On the right panel: a MODIS image where field data sites (Castellammare, Gela and Augusta gulfs) are highlighted by white rectangles; whereas sites used for water quality comparison (Gulf of Palermo vs. Lo Zingaro; Gulf of Milazzo vs. Tindari; Gulf of Gela vs. Pozzallo) are shown with red (polluted) and cyan (unpolluted) dots.

Since the average diffuse attenuation coefficient K_d for red wavelength were approximately $\sim 0.18 \text{ m}^{-1}$, the bottom influences the water leaving radiance up to a distance from the coast of 750 m at least, in which depths are ~ 15 , ~ 10 and ~ 30 m in Castellammare, Gela and Augusta gulfs respectively. For this reason turbidity retrieved by remote sensing should not be accurate within this distance from the shoreline; consequently, samples were acquired between 1.5 km up to 5 km from the coastline, and MODIS images having 1 km spatial resolution have been processed only for no-land pixels.

Castellammare gulf is the deeper inlet of the Sicilian coast, having a length ~ 60 km and a distance between the delimiting headlands (chord) of about 30 km.

Gela gulf has a coastline extending for about 75 km with a chord greater than 65 km. Water is prevalently shallow with a sandy bottom and several seaports and industrial activities characterize the coast. The latter includes one of the bigger petrochemical refineries of the Mediterranean area.

In addition, Augusta gulf has a coastline characterized by intensive chemical, petrochemical activities and several torrents flowing into the gulf. It extends for about 30 km with a chord greater than 15 km. Differently than the other gulfs, Augusta gulf is mainly occupied by port structure (the “Rada di Augusta”).

The choice of the sites was based on the NT variability, as it can be preliminary analyzed on the remotely sensed maps retrieved applying the Chen et al. [2007] empirical relationship and parameters.

Sampling points were positioned along two transects having a distance of ~ 3.50 Km (Fig. 2). Each transect is almost orthogonal to the coastline and includes 3-4 sampling points. Within Castellammare gulf (Fig. 2, left panel), a further sampling point has been chosen between the two transects in order to evaluate peculiar characteristics of a fish factory (point C4).

Once the calibration has been applied, a comparison among the average turbidity of areas characterized by high and low anthropic impact has been performed on three different parts of the Sicilian coastal zone (north-east, south-east and north-west).

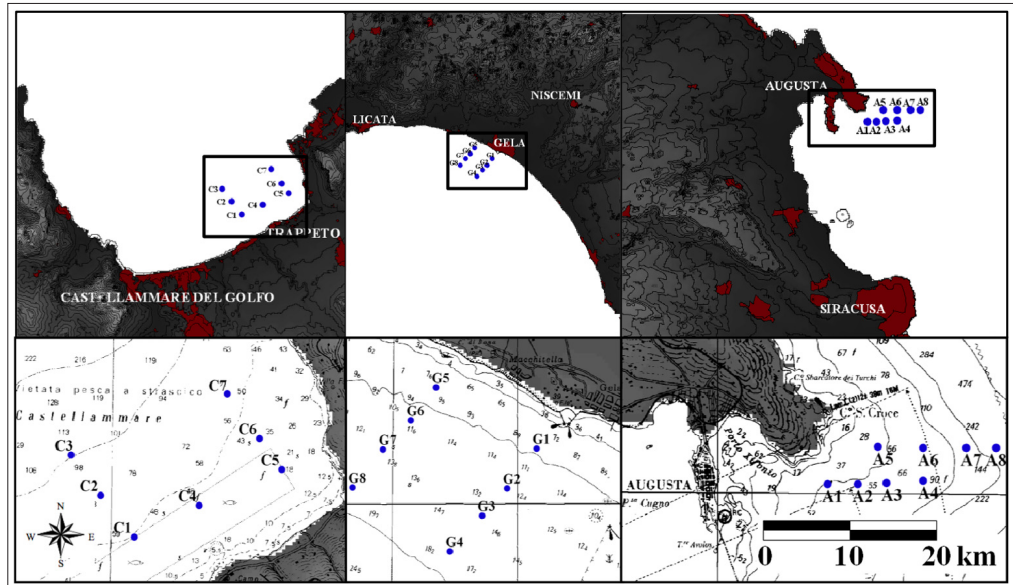


Figure 2 - Geo-location of the sampling points within Castellammare (left panel, from C1 to C7), Gela (central panel, from G1 to G8) and Augusta (right panel, from A1 to A8) gulfs, over-imposed on nautical maps. The land domain of the maps is made up of a digital elevation model (DEM, in grey-scale) with main urban centres superimposed (in purple).

The gulfs of Milazzo, Gela and Palermo have been chosen (Fig. 1, red dots), among areas having high human pressure, with the aim to represent polluted and hence, but not necessarily, turbid waters. Average surface water *NTs* of these gulfs have been compared to those of areas that should correspond to clear waters: Tindari, Pozzallo and Lo Zingaro natural reserve respectively (Fig. 1, cyan dots). Average values have been evaluated over areas extending for approximately 5000 Km².

Materials

The dataset includes *in situ* data from three campaigns carried out during the first week of July, August and September 2008 respectively; each day between 8.00 and 13.00 (local time). Field data were positioned in UTM WGS84 using an EGNOS-enabled Magellan Meridian Platinum GPS device.

Spectroradiometric measurements

Underwater spectral irradiances and in-air upwelling spectral radiances were acquired using an Analytical Spectral Devices FieldSpec® HandHeld spectroradiometer operating between 325 and 1075 nm with a spectral resolution of 1.5 nm. A 10-meter long fiber optic cable, fitted with an underwater cosine diffuser probe (UW RCR with Radiometric Calibration), was used to acquire underwater irradiances at 11 depths from just below the water's surface, up to 5.5 meters.

Spectral radiances were acquired using a 25 degree optic lens with a ~ 1 m distance from the target. Reflectance was referenced to a calibrated white Labsphere Spectralon reference

panel. Spectral reflectance measurements have been carried out along two transects in each gulf for each sampling period.

Nephelometric turbidity measurements

Turbidimetry enables to assess water turbidity by means of the absorption and refraction properties at specific wavelengths.

Nephelometric Turbidity (*NT*) is generally measured in *Nephelometric Turbidity Units* (NTUs) as specified by *United States Environmental Protection Agency*. The unit of measurement has been standardized on the formazin polymer compound, developed to match the gravimetric mass of Kaolin clay, so that a 1 NTU \approx 1 mg l⁻¹ (of Kaolin within water).

In order to measure suspended particulates in coastal waters a nephelometer of the YSI 6-Series has been used (YSI incorporated). Its working principle is based on a near infrared source beam (830-890 nm) emitted by a Light Emitting Diode (LED) and high sensitivity light detector set to one side (at 90°) recording the scattered radiation.

The probe has got a rotating system in order to remove the fouling attaching on the lenses. The instrument has been calibrated before each field data acquisition in three points of the measuring scale (0, 10 and 100 NTU): since water turbidity was very low the systematic error was $\sim \pm 5\%$. Data were acquired for ~ 180 seconds with a sampling frequency equals to 60 Hz, at 6 water depths between 0.5 and 5.5 m.

Remotely sensed data

MODIS acquires in 36 spectral bands: 21 between 0.4 and 3.0 μm , and the remaining 15 between 3.0 and 14.5 μm . Images are characterized by a 2300 km of swath width and a spatial resolution of 250 m for the first two bands, 500 m for the next 5 bands and 1 km for the remaining 29 bands, with a temporal resolution varying between 1 and 2 days. We chose not to use high level products since their calibration was considered not to be adequate to fit local field measurements. The images have been automatically georeferenced using the Geographic Lookup Table (GLT) obtained from the latitude longitude dataset of the MOD03 product. An automatic system to georeference and to calibrate the images has been implemented. The programming routines have been developed using the IDL programming language, allowing the simultaneous computation of the whole time series of images. The dataset includes raw images (MOD02 - L1B) acquired monthly between February 2000 and September 2008.

Methods

NTU modelling

An empirical relationship, calibrated on the estuarine area of Tampa bay in Florida, is widely applied to map water surface turbidity from MODIS images [Chen et al., 2007]. This relationship uses the remote sensing reflectance R_{rs} (sr⁻¹) from the red band (centred on 645 nm), computed as ratio between reflected radiance and downwelling irradiance. Within the estuarine area of Tampa bay, R_{rs} (645) have shown values ranging between 0.001 and 0.008 sr⁻¹, corresponding to *in situ* NT ranging between 0.9 and 8.0 NTU. Empirical evidence ($n=43$) suggested a power relationship to better fit *in situ* data [1]:

$$NT = a \cdot R_{rs}(645)^b \quad [1]$$

where the calibration coefficients $a=1203.9$ and $b=1.087$ were characterized by a determination coefficient $r^2=0.73$.

Since the direct application of the above reported empirical relationship did not provide accurate estimations of surface NT (see Results section) within the Sicilian coastal zone, this research is aimed to calibrate it using *in situ* data acquired in different sites and months. Within this research, reflectance R (-) has been firstly calculated rationing upwelling and downwelling radiances, then the R_{rs} has been retrieved.

NT sites comparison

Mapping of surface water turbidity of the whole Sicilian coastal area over a long period can be achieved using optical remotely sensed images and a reflectance vs. NT relationship.

A statistical analysis allowed evaluating and comparing water quality in three pairs of sea-zones around Sicily that are supposed to be characterized by low and high human impacts. The correlation between time series over different zones has been analysed by means of the Pearson product-moment correlation coefficient, r , which is recognized to be suitable for this kind of analysis since it is sensitive to a linear relationship between the NT measured *in situ* and the one estimated through remotely sensed images. Since correlation coefficient approximately follows Student's t-distribution, the significance of the estimation has been assessed by means of probability distribution analysis of r for $P = 0.01$ (high significance level). The comparison between r evaluated from the experimental data with the ones retrieved from the probability distribution has been carried out for given degrees of freedom: $GL = n-2$ (number of observation pairs minus the numbers of involved variables).

In order to objectively compare those linear relationships among the three pairs of time series, it was necessary to estimate the interval around the sample mean, \bar{x} , which includes the population mean, μ , for given confidence level.

The confidence intervals, I_c , are given by [2]:

$$I_c = \bar{x} \pm k(\alpha) \frac{\sigma}{n} \quad [2]$$

where σ is the standard deviation, n is the number of samples, k is a function of the confidence level ($1-\alpha$).

Field data statistical analysis: the One-way ANOVA

In order to calibrate reflectance to NT relationship, turbidity samples are needed. However, it should be checked whereas samples, acquired within different sites and months, belong to the same population or not in order to correlate turbidity data with spectroradiometric data. The analysis can be carried out either for given acquisition time or for acquisition site: in the first the spatial homogeneity of turbidity within the three sites for given acquisition time will be evaluated; in the second case the temporal variation of turbidity during the three field campaigns for given field site will be understood.

Statistical analysis has been performed by means of a one-way ANOVA (ANalysis Of Variance) [Kirk, 1995] comparing the variance within the samples to the variance among the means.

ANOVA provides an F statistic, the ratio of the variance computed among the means to the variance within the samples. Following central limit theorem, if the group means belong to the same population, the variance between the group is supposed to be lower than the variance within, quantifying the spread of NT within groups. A higher value of the F statistic than its critical value F_{crit} implies significant differences between the groups, meaning that the samples do not belong to the same population (null hypothesis).

The algorithm has been calibrated using a least-squares analysis by minimizing the total variance between *in situ* NT (x -axis) and estimated NT (y -axis). To this aim *in situ* data have been spatially grouped and left temporally separated.

Once the NT relationship has been calibrated using *in situ* data, NT maps have been retrieved using also literature parameters (NT_{lit}) in order to compare for each gulf and over three months the two approaches. The comparison is shown in terms of time behaviour of average NT , 2nd and 98th percentile; and in terms of percentage difference [3]:

$$d_p(\%) = \frac{|NT - NT_{lit}|}{\left(\frac{NT + NT_{lit}}{2}\right)} \cdot 100 \quad [3]$$

Results

In the following section, sites characterized by different human pressure are comparatively analysed in terms of surface water turbidity.

Comparative analysis

The comparative analysis between NT retrieved on sites characterized by low and high anthropic pressure shows that marine areas close one to each other such as Lo Zingaro nature reserve and Palermo gulf, Tindari and Milazzo gulfs, Pozzallo and Gela gulfs, show high correlation coefficients ($r > 0.76$), whereas areas far one from each other show a lower correlation (0.41 - 0.61). The correlations significance is reached for $r > 0.145$.

The trend line (Fig. 3, central line) shows that turbidity of Milazzo (left panel, y -axis) is on average greater than the Tindari one (x -axis) only below a threshold value and the confidence interval includes the bisector line and does not allow to reach a similar conclusion as for SE sector. Slope, m , intercept, q , and determination coefficient, r^2 , of the regression line were approximately: 0.87, 0.97 and 0.73 respectively.

The regression line (Fig. 3, central panel, y -axis) shows that the turbidity of Gela gulf is on average greater than the one in Pozzallo (x -axis) for NT values lower than a threshold: this seems reasonable since Gela gulf is more prone to anthropic pressure. On average turbidity of Gela gulf is greater than the Pozzallo one ($m \approx 0.60$, $q \approx 2.35$, $r^2 \approx 0.57$), with a peak frequency in August.

Turbidity of Palermo area (Fig. 3, right panel, y -axis) is greater than the Lo Zingaro one (x -axis) for NT value less than a threshold ($m \approx 0.67$, $q \approx 2.14$, $r^2 \approx 0.59$). On average, the turbidity of Palermo is greater than the Lo Zingaro area during spring and summer seasons (April and August in particular).

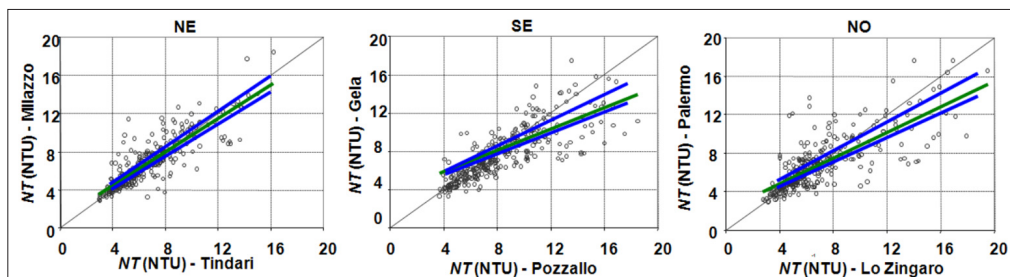


Figure 3 - Nephelometric Turbidity (NTU) of Milazzo gulf vs. Tindari (North-East sector) (left panel); Gela gulf vs. Pozzallo area (South-East sector) (central panel); and Palermo gulf vs. Lo Zingaro natural reserve (North-West sector) (right panel). Blue lines indicate the upper and lower confidence lines; green line is the dispersion trend line.

The ranges of turbidity within the two sectors (SE and NW) are similar (between 3 and 19 NTU) whereas the upper limit decreases in NE sector (about 13 NTU). These values are much higher than the ones measurable on site (see Nephelometric properties section), highlighting the need to calibrate equation [1] for quantitative analysis.

This paper provides calibration coefficients to be applied approximately between July and September.

Water spectroradiometric properties

In July, spectral reflectance within the Castellammare gulf reached maxima at ≈ 480 nm, ranging between $\sim 2.5\%$ and $\sim 4.0\%$ with lower values characterizing the C4 sampling point, located in between main transects (see Fig. 2 left panel) close to a fish factory. In August, spectral reflectance (≈ 490 nm) had maxima higher than the ones taken in July, ranging between $\sim 3.5\%$ and $\sim 7.0\%$; lower values have been found within the area of the fish factory as in July.

Within Gela gulf, spectral signatures in August were characterized by maxima (ranging between ≈ 480 and ≈ 500 nm) similar to the ones in July according to literature findings for low chlorophyll-a concentration (e.g. $3 \mu\text{g l}^{-1}$ in Gower and King, [2004]). Values ranged between $\sim 3.0\%$ and $\sim 4.0\%$ with lower values characterizing the south-east transect close to the coastline. Spectral signatures from the north-west transect shown noisy values at ≈ 350 nm and in the near infrared. Spectral reflectance ranging between ≈ 480 and ≈ 500 nm highlighted a maximum in September similar to the one characterizing previous months. Values ranged between $\sim 3.0\%$ and $\sim 5.0\%$ with lower values characterizing the off shore sampling points.

Within the Augusta gulf, spectral signatures in July had maxima lower than reflectance measured in Gela. Those values ranged between $\sim 2.5\%$ and $\sim 3.5\%$ with lower values characterizing sampling points closer to the coastline (A1 and A5). The second peak (broadly at 530 nm) was less evident than the one in Gela, like in Castellammare, according to literature findings for low chlorophyll-a concentration [Gower et al., 1999; Gower and King, 2004]. August spectral reflectances ranged between $\sim 2.5\%$ and $\sim 4.0\%$, while September signatures had lower values than the ones in August ($\sim 3.0\%$ - $\sim 4.5\%$).

Nephelometric properties

Nephelometric turbidity shown maximum values during the first sampling period, where the range of variability was also higher: minimum has been measured in Augusta (1.85 NTU) while maximum has been found in Gela (5.72 NTU). *NT* decreased on the average in August, reaching minimum values in September with an absolute minimum measured both in Gela and Castellammare (1.27 NTU). Statistical values of *NT* dataset are listed in Table 1.

Table 1 - *NT* average (μ) and standard deviation (σ) in the three gulfs of Castellammare, Augusta and Gela in July, August and September 2008.

	Castellammare		Gela		Augusta	
	μ (NTU)	σ (NTU)	μ (NTU)	σ (NTU)	μ (NTU)	σ (NTU)
Jul	2.76	0.42	2.67	0.52	2.46	0.33
Aug	2.60	0.25	2.26	0.37	2.04	0.26
Sep	2.12	0.30	1.92	0.33	1.93	0.17

Algorithm calibration

Pre-calibration: One-way ANOVA

The analysis has been carried out on MODIS data previously calibrated in *NT* using Chen et al. [2007] relationship, and comparing their value with *NT* acquired on site.

The analysis allows evaluating if samples acquired in different sites have turbidity characteristics to be considered belonging the same population (like they were acquired in the same site). The analysis shows the three samples belong the same population ($F=1.31 < F_{crit} = 3.18$) (Tab. 2), therefore they can be jointly treated from a spatial point of view.

The analysis allows also understanding if samples acquired during three subsequent months can be used jointly as belonging the same population (like they were acquired at the same time). Differently than the previous case, the three samples do not belong the same population ($F=13.07 > F_{crit} = 3.17$), consequently *in situ* data cannot be grouped together on a temporal basis (Tab. 3). Table 2 and 3 report for completeness the sum of squares, *SoS*, the degree of freedom, *dof*, and the mean square.

Summarizing, *in situ* data can be grouped together independently their spatial attribute, however they must be left temporally separated.

Table 2 - Field data spatial analysis: One-way ANOVA statistics.

	Variance source	<i>SoS</i>	<i>dof</i>	<i>MS</i>	<i>F</i>	Significance value	<i>F_{crit}</i>
Field data	between groups	0.96	2	0.48	1.31	0.28	3.18
	within groups	18.78	51	0.37	-	-	-
	total	19.74	53	-	-	-	-
<i>NT</i>	between groups	2.54	2	1.27	2.51	0.09	3.18
	within groups	25.80	51	0.51	-	-	-
	total	28.34	53	-	-	-	-

Table 3 - Field data temporal analysis: One-way ANOVA statistics.

	Variance source	<i>SoS</i>	<i>dof</i>	<i>MS</i>	<i>F</i>	Significance value	<i>F_{crit}</i>
Field data	between groups	7.00	2	3.50	13.07	0.00	3.17
	within groups	14.19	53	0.27	-	-	-
	total	21.19	55	-	-	-	-
NT	between groups	2.08	2	1.04	2.10	0.13	3.17
	within groups	26.28	53	0.50	-	-	-
	total	28.36	55	-	-	-	-

Calibration

The ANOVA analysis shows that data acquired in different gulfs can be grouped together (23 samples), whereas they should be left sub-divided depending on the month of acquisition (3 datasets), then three datasets of calibration coefficients were obtained. Time series data of the three pairs of values (a pair of measured data and estimated values from water reflectance, for each site) have been plotted on a Cartesian diagram to retrieve a linear relationship using the least square method.

The correlation between time series over different zones has been analyzed by means of the Pearson coefficient, r . The significance of the estimation has been assessed by means of probability distribution analysis of r for $P = 0.01$ (high significance level) and $P = 0.05$ (good significance level). The comparison between r value retrieved from experimental data and the one retrieved from the Student's t -distribution (r^P where the superscript P denotes the significance level) has been carried out for fixed degrees of freedom: $GL = n-2$ (number of observation pairs minus the numbers of involved variables). In the present case $GL=21$ and $r^{0.01} = 0.526$ and $r^{0.05} = 0.413$.

Furthermore, the significance of the linear equation slope has been assessed through the T-Student test, aimed to verify if the statistical observed value t , given by the ratio between the slope and its standard error, is greater than the critical value t^P for chosen significance level P and for given degrees of freedom and two tales T-Student distribution.

In the present study $t^{0.01} = 2.831$ and $t^{0.05} = 2.079$. A comparison between calibration coefficients retrieved from field spectroradiometric and NT data and the ones given by Chen et al. [2007] is shown in Table 4.

Table 4 - Reflectance vs. NT calibration coefficient from *in situ* data (July, August and September) and the ones given by Chen et al. [2007].

Calibration coefficients	July	August	September	Literature
<i>a</i>	1203.9	1203.9	1203.9	1203.9
<i>b</i>	1.112	1.399	1.290	1.087

The on-site calibration allows estimating the spatial distribution of the surface NT. Retrieved values well agree with *in situ* data. Slope and intercept (m , q) assume the values of (1.04, 0.06), (0.77, 0.37), (1.01, 0.04) in July, August and September respectively; determination

coefficient, r^2 , is approximately equal to 0.52 in July and 0.83 in August and September. Whereas Chen et al. [2007] equation overestimates NT , especially in August and September (Fig. 4, central and right panels). Slope and intercept are satisfactory in July (0.92, -0.09), but they highlight a poor performance of the literature equation (3.07, 1.69), (2.66, 0.32) in August and September respectively, even if the determination coefficient remains quite high during the three months (0.52, 0.82 and 0.85).

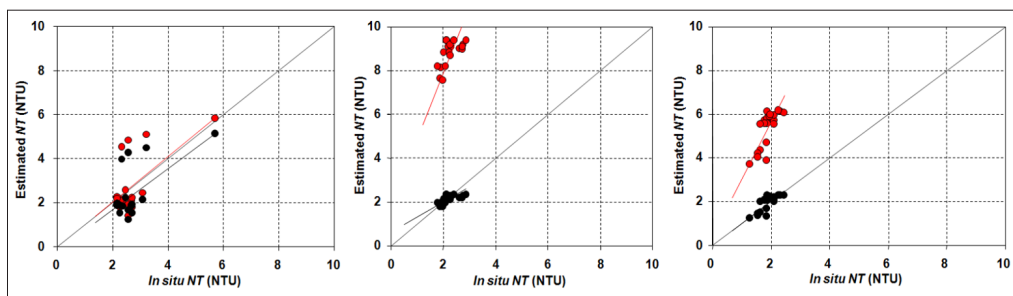


Figure 4 - Remotely sensed NT vs. *in situ* NT (NTU) for July (left panel), August (central panel) and September 2008 (right panel). NT values estimated through Chen et al. equation [2007] are plotted with filled red circles, whereas those obtained through the *in situ* calibration are represented in black.

The coefficient a did not change during the acquisition period, while coefficient b reached its maximum value in August. Nevertheless, the latter was always higher than the one found in literature [Chen et al., 2007].

The analysis shows that data acquired in different gulfs should be grouped together (23 samples), while they must be left ungrouped depending on the month of acquisition (3 datasets). Once the calibration has been carried out, the three temporal clusters move closer (not shown here). Coastal sea waters show a reflectance peak ranging between ≈ 480 and ≈ 500 nm and very low chlorophyll- a concentration (0.1 - $0.5 \mu\text{m l}^{-1}$), while the second peak at 550 nm is not always evident.

Turbidity temporal and spatial distribution

Data analysis has been carried out on the average NT and standard deviation for each acquisition and in each gulf. These statistics values are computed over the area delimited by two external promontories (Fig. 5).

The NT range of variability decreased in comparison to the one obtained using the literature parameters from 5.4 to 3.3 NTU, indeed the average NT ranges between ~ 0.3 and ~ 3.6 NTU (whereas using literature parameters, NT would range between ~ 0.9 and 6.3 NTU).

Average values are generally lower than the ones obtained by using literature parameters, differences are the lowest in July (between 0.16 and 0.40 NTU) and the highest in August (between 2.42 and 3.82 NTU).

NT images retrieved using both literature and parameters *in situ* calibrated over Castellammare, Augusta and Gela gulfs and, for each gulf, in July, August and September have been compared in terms of d_p (%) (see eq. 3). Results are shown in Table 5.

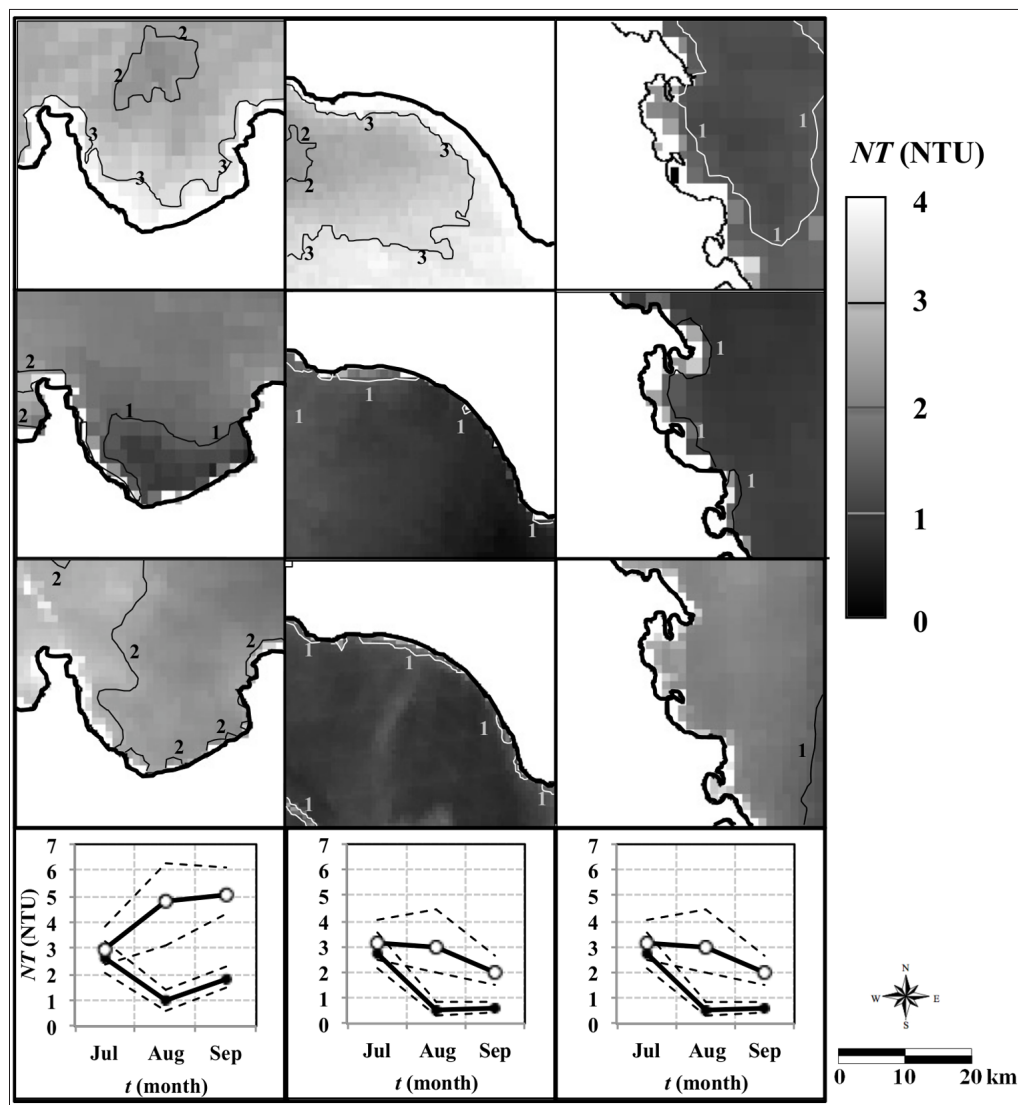


Figure 5 - NT (NTU) in Castellammare (left panel), Gela (central panel) and Augusta (right panel) gulfs, in July (upper panels), August (upper centre panels) and September (lower centre panels). Lower panels report the temporal behaviour of average values using the parameters calibrated *in situ* (black filled dots, continuous line) and the literature parameters (white filled dots), the temporal behaviour of average values using the literature parameters, and 2nd and 98th percentiles (lower and upper dashed lines respectively).

Low μ_{dp} have been found in September (12.3% on average), it reaches high values in August (109.6%), and then decreases again in September (88.8%). However d_p reached even more higher values (e.g. the 2nd percentile of d_p within the Gela gulf was 146.1% in August). These values highlight the need of an *in situ* calibration for using NT for quantitatively monitoring.

Table 5 - Percentage difference d_p (%) of the average values μ_{dp} between *NT* images retrieved using calibrated *in situ* vs. literature parameters. Between brackets the percentage difference of the 2nd and 98th percentiles respectively of μ_{dp} .

	July	August	September
<i>Castellammare</i>	12.2 (14.1-14.6)	110.0 (139.0-128.2)	86.3 (96.9-91.4)
<i>Gela</i>	12.0 (14.2-13.2)	115.3 (146.1-133.7)	90.5 (111.3-103.8)
<i>Augusta</i>	12.7 (16.1-14.8)	103.5 (142.2-129.3)	89.5 (98.3-104.4)

Conclusions

The comparison among surface water turbidity of areas having different anthropic impact shows that in SE sector of the island of Sicily nephelometric turbidity concentration is higher than in other sites only during some periods of the year (spring-summer and autumn respectively) even if it is theoretically more influenced by human activities.

The confidence interval characterising the sample of the NE sector does not allow generalising the conclusions to the whole population.

In situ data, acquired during spring and summer period, have been used to locally improve the retrieval of water surface nephelometric turbidity through satellite images. Model calibration for Mediterranean coastal zones allows mapping water quality with higher accuracy than NASA high-level products, since the latter are calibrated at global scale and the relationship between spectral reflectance and water composition (and consequently water turbidity) is typically *in situ* dependent. Consequently, the use of high-level products for regional studies could lead to inaccurate conclusions.

Pre-calibration statistical analyses show that field data should be spatially grouped and temporally divided. Calibration shows that *a* coefficient is constant in time (1203.9), differently from coefficient *b* that increases from July to August (1.112 to 1.399) and then decreases during last month (down to 1.290), always showing values higher than the one found in literature (1.087). Notably, coastal seawaters show a reflectance peak between ≈ 480 and ≈ 500 nm probably related to low chlorophyll-a concentration, whereas a second peak at 550 nm is not always evident.

The implemented techniques and products can be used to localise anomalies and trends for water quality parameters at regional scale.

Even if the parameters range within the literature values, the model calibration for Mediterranean area gives more accurate results compared to the ones obtained using literature parameters [e.g. Chen et al. 2007].

The results here obtained show a good agreement between measured and image-retrieved water quality parameters, especially in September (*m*, *q* and *r*² were respectively ≈ 1.04 , ≈ 0.04 and ≈ 0.83).

The evaluation of percentage difference between *NT* images retrieved using calibrated *in situ* vs. literature parameters (up to $\approx 146\%$, in August, 2nd percentile) highlights the need of an *in situ* calibration for using *NT* for quantitatively monitoring.

Further measurement campaigns are planned to build up a robust database of sea-truth and satellite images data.

Acknowledgement

This research was partially funded by the ARPA (Agenzia Regionale per la Protezione dell'Ambiente) of the Sicilian Regional Government within the "Monitoraggio della qualità delle acque marino-costiere siciliane con l'ausilio di tecniche di telerilevamento" Project (Monitoring sea-coastal waters in Sicily using remote sensing techniques). Authors thank G. Sarà, of the Department of Ecology of the University of Palermo, for helping them in the field data interpretation, and A. Scordo, M. Tulone and A. Vitagliano for field data acquisition.

References

- Anthony K.R.N., Ridd P.V., Orpin A.R., Larcombe P., Lough J. (2004) - *Temporal variation of light availability in coastal benthic habitats: Effects of clouds, turbidity, and tides*. Limnology and Oceanography, 49 (6): 2201-2211. doi: <http://dx.doi.org/10.4319/lo.2004.49.6.2201>.
- Chen Z., Muller-Karger F., Hu C. (2007) - *Remote sensing of water clarity in Tampa Bay*. Remote Sensing of Environment, 109: 249-259. doi: <http://dx.doi.org/10.1016/j.rse.2007.01.002>.
- Cloern J.E. (1987) - *Turbidity as a control on phytoplankton biomass and productivity in estuaries*. Continental Shelf Research, 7 (11): 1367-1381. doi: [http://dx.doi.org/10.1016/0278-4343\(87\)90042-2](http://dx.doi.org/10.1016/0278-4343(87)90042-2).
- Cloern J.E., Powell T.M., Huzzey L.M. (1989) - *Spatial and temporal variability in South San Francisco Bay. II. Temporal changes in salinity, suspended sediments, and phytoplankton biomass and productivity over tidal time scales*. Estuarine, Coastal and Shelf Science, 28: 599-613. doi: [http://dx.doi.org/10.1016/0272-7714\(89\)90049-8](http://dx.doi.org/10.1016/0272-7714(89)90049-8).
- Cole B.E., Cloern, J.E. (1987) - *An empirical model for estimating phytoplankton productivity in estuaries*. Marine Ecology- Progress Series, 36: 299-305. doi: <http://dx.doi.org/10.3354/meps036299>.
- Curran P.J., Novo E.M.L.M. (1988) - *The relationship between suspended sediment concentration and remotely sensed spectral radiance: a review*. Journal of Coastal Research, 4: 351-368.
- Doxaran D., Froidefond J.M., Lavender S., Castaing P. (2002) - *Spectral signature of highly turbid waters. Application with SPOT data to quantify suspended particulate matter concentrations*. Remote Sensing of Environment, 81: 149-161. doi: [http://dx.doi.org/10.1016/S0034-4257\(01\)00341-8](http://dx.doi.org/10.1016/S0034-4257(01)00341-8).
- Doxaran D., Castaing, P., Lavender S.J. (2006) - *Monitoring the maximum turbidity zone and detecting fine-scale turbidity features in the Gironde estuary using high spatial resolution satellite sensor (SPOT HRV, Landsat ETM+) data*. International Journal of Remote Sensing, 27: 2303-2321. doi: <http://dx.doi.org/10.1080/01431160500396865>.
- Fisher T.R., Gustafson A.B., Sellner K., Lacouture R., Haas L.W., Wetzel R.L., Magnien R., Everitt D., Michaels B., Karrh R. (1999) - *Spatial and temporal variation of resource limitation in Chesapeake Bay*. Marine Biology, 133 (4): 763-778. doi: <http://dx.doi.org/10.1007/s002270050518>.
- Gower J., King S. (2004) - *Satellite fluorescence as a measure of ocean surface chlorophyll*. Gayana suppl. t.I. Proc. 68 (2): 252-258.
- Gower J.F.R., Doerffer R., Borstad G.A. (1999) - *Interpretation of the 685 nm peak in water-leaving radiance spectra in terms of fluorescence, absorption and scattering, and*

- its observation by MERIS*. International Journal of Remote Sensing, 9: 1771-1786. doi: <http://dx.doi.org/10.1080/014311699212470>.
- Harrington J.A.Jr., Schiebe F.R., Morrison F.E. (1989) - *Monitoring lake recovery using Landsat MSS*. International Association of Hydrological Sciences Publication, 182: 143-150.
- Heyes A., Miller C., Mason R.P. (2004) - *Mercury and methylmercury in Hudson River sediment: Impact of tidal resuspension on partitioning and methylation*. Marine Chemistry, 90 (1-4): 75-89. doi: <http://dx.doi.org/10.1016/j.marchem.2004.03.011>.
- Kirk R.E. (1995) - *Experimental design: Procedures for the behavioral sciences*. Third Edition, Pacific Grove, CA, USA: Brooks/Cole.
- Maltese A., Capodici F., Ciralo G., Granata A., La Loggia G. (2011) - *A diachronic analysis of estuarine turbidity due to a flood following an extreme rainfall event*. SPIE Proceedings - Remote Sensing for Agriculture, Ecosystems, and Hydrology XIII, 8174: 81741C-1 - 81741C-8.
- Miller R.L., Mckee B.A., D'Sa E. (2005) - *Monitoring bottom sediment resuspension and suspended sediments in shallow coastal waters*. In R. L. Miller (Ed.), Remote sensing of coastal aquatic environments, pp. 259-276.
- Moore K.A., Wetzel R.L., Orth R.J. (1997) - *Seasonal pulses of turbidity and their relations to eelgrass (Zostera marina L.) survival in an estuary*. Journal of Experimental Marine Biology and Ecology, 215 (1): 115-134. doi: [http://dx.doi.org/10.1016/S0022-0981\(96\)02774-8](http://dx.doi.org/10.1016/S0022-0981(96)02774-8).
- Pennock J.R., Sharp J.H. (1994) - *Temporal alternation between light limitation and nutrient-limitation of phytoplankton production in coastal plain estuary*. Marine Ecology-Progress Series, 111 (3): 275-288. doi: <http://dx.doi.org/10.3354/meps111275>.
- Reddy M.A., Srinivasulu S. (1994) - *Comparison of IRS-IB LISS-IIA pixel array sizes for estimating suspended solids concentration in Hussain Sagar lake, Hyderabad, India-a statistical approach*. International Journal of Remote Sensing, 15: 3693-3706. doi: <http://dx.doi.org/10.1080/01431169408954352>.
- Ruddick K., Park Y., Nechad B. (2003) - *MERIS imagery of Belgian coastal waters: Mapping of suspended particulate matter and chlorophyll-a*. MERIS user workshop, 10-13th of November. Frascati: ESA, SP-549.
- Schoellhamer D.H. (1996) - *Anthropogenic sediment resuspension mechanisms in a shallow microtidal estuary*. Estuarine, Coastal and Shelf Science, 43 (5): 533-548. doi: <http://dx.doi.org/10.1006/ecss.1996.0086>.
- Stumpf R.P., Pennock J.R. (1989) - *Calibration of a general optical equation for remote sensing of suspended sediments in a moderately turbid estuary*. Journal Geophysical Research, 94 (C10): 14363-14371. doi: <http://dx.doi.org/10.1029/JC094iC10p14363>.
- Uncles R.J., Stephens J.A., Smith R.E. (2002) - *The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time*. Continental Shelf Research, 22: 1835-1856. doi: [http://dx.doi.org/10.1016/S0278-4343\(02\)00041-9](http://dx.doi.org/10.1016/S0278-4343(02)00041-9).
- Wolanski E., Spagnol S. (2003) - *Dynamics of the turbidity maximum in King Sound, tropical Western Australia*. Estuarine, Coastal and Shelf Science, 56 (5-6): 877-890. doi: [http://dx.doi.org/10.1016/S0272-7714\(02\)00214-7](http://dx.doi.org/10.1016/S0272-7714(02)00214-7).

Received 26/06/2012, accepted 09/01/2013