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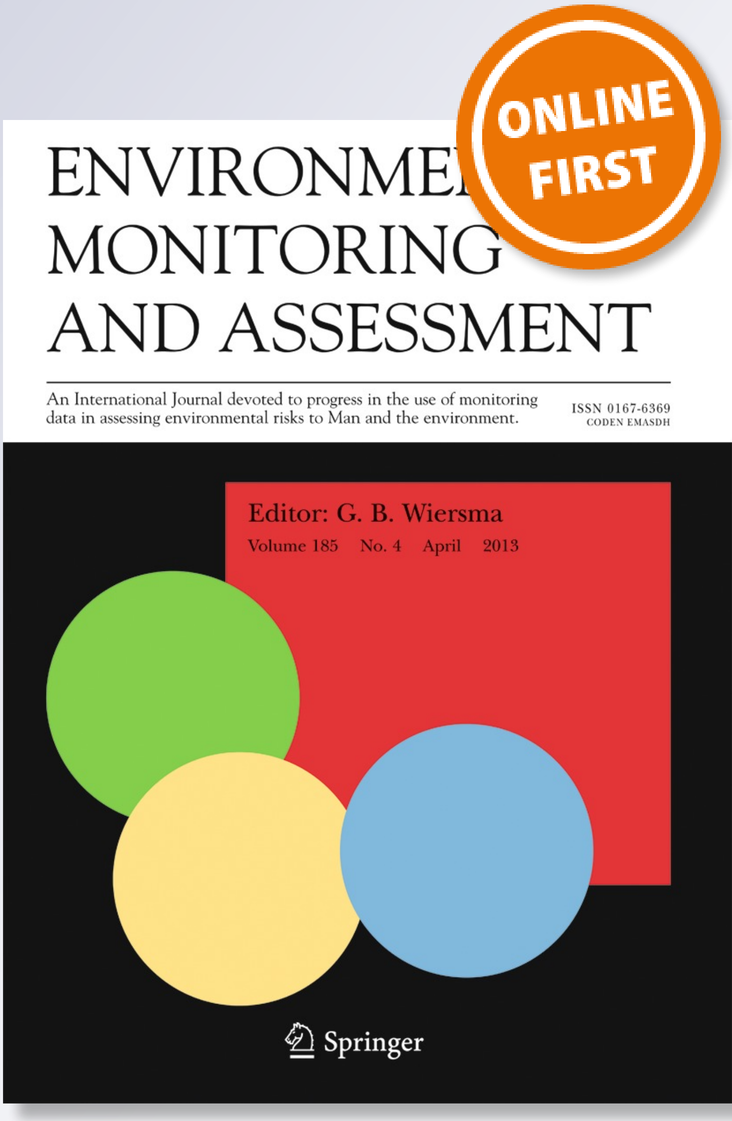

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Abstract The Bormida River Basin, located in the northwestern region of Italy, has been strongly contaminated by the ACNA chemical factory. This factory was in operation from 1892 to 1998, and contamination from the factory has had deleterious consequences on the water quality, agriculture, natural ecosystems and human health. Attempts have been made to remediate the site. The aims of this study were to use high-resolution satellite images combined with a classical remote sensing methodology to monitor vegetation conditions along the Bormida River, both upstream and downstream of the ACNA chemical factory site, and to compare the results obtained at different times before and after the remediation process. The trends of the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) along the riverbanks are used to assess the effect of water pollution on vegetation. NDVI and EVI values show that the contamination produced by the ACNA factory had less severe effects in the year 2007, when most of the remediation activities were concluded, than in 2006 and 2003. In 2007, the contamination effects were noticeable up to 6 km downstream of the factory, whereas in 2003 and 2006 the influence range was up to about 12 km downstream of the factory. The results of this study show the effectiveness of remediation activities that have been taking place in this area. In addition, the comparison between NDVI and EVI shows that the EVI is more suitable to characterise the vegetation health and can be considered an additional tool to assess vegetation health and to monitor restoration activities.

Keywords NDVI · EVI · Satellite remote sensing · Water pollution · High-resolution images

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Introduction

Industrial development in Europe since the beginning of the nineteenth century has incurred the ecological cost of the degradation of natural systems. Whilst the Industrial Revolution generated positive changes for the economy, negative impacts were incurred on the environment, such as the depletion of natural resources, pollution of air, water and soil, and the release of greenhouse gasses which contribute to global

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warming, among others (Burton 2003). The ecological impacts of past industrial development can be seen even in the present (Rothwell et al. 2008).

New industries that emerged during the Industrial Revolution did not make any effort to reduce contamination, and rivers were used as an inexpensive way to discharge waste. Toxic substances have accumulated in rivers over the years, leading to soil contamination occurring over a wide area during flooding events.

This paper presents the case study of the ACNA chemical factory which has been discharging wastewater into a small river in the northwestern region of Italy for over a century, leading to severe pollution and damage to human health in the surrounding region. The factory was closed down in 1998 for this reason, and reclamation activities were started that lasted for several years. The affected area has been used as a test site for various scientific studies aimed at improving the assessment methods (Marengo et al. 2006; Semenzin et al. 2008) and remediation techniques (Baldi et al. 2007). Different approaches to assessment techniques can be found in the literature. Chemical analyses of water and soil samples using standard procedures and methodologies have been used to assess the levels of pollution (Marengo et al. 2006; Zerbinati et al. 1997). In addition, biomonitoring techniques have been applied, clearly showing the unhealthy status of both plant (Vallino et al. 2006) and animal life (Avidano et al. 2005) directly related to high contamination.

A method of assessment of natural resource health over spatial and temporal scales is based on high-resolution satellite earth observation images (Rastmanesh et al. 2010; Sass et al. 2007). Satellite images can provide accurate information regarding ground conditions. These data are useful for recognizing patterns of change and could potentially be of high value for managing natural resources (Rodríguez et al. 2007).

Furthermore, regional and local land reclamation programmes are increasingly incorporating remotely sensed imagery to monitor vegetation dynamics. Spectral vegetation index data have been used to monitor vegetation conditions (Willem et al. 2006).

The temporal resolution of remote sensing datasets enables the study of dynamic phenomena such as ecosystem recovery over a multiple-year period. Previous research on the use of remotely sensed imagery in monitoring regeneration patterns in Mediterranean ecosystems has been presented by many authors (Diaz-Delgado and Pons 2001; Riano et al. 2002; Viedma et al. 1997).

Moreover, remote sensing techniques can provide both spatial and temporal surface water quality parameters. Remote sensing makes it possible to monitor the landscape effectively and efficiently, identifying water bodies with significant water quality problems, so that it can support developing water management strategies. Although the methods to retrieve water quality information from remote sensing data might not be as precise as traditional methods, they are time- and cost-efficient over a large area and can provide the opportunity for regular observation of even very remote regions (Seker et al. 2003). Therefore, remote sensing techniques have been widely used in estimating the pollution situation of surface waters (Ekstrand 1992; Giardino et al. 2010; Gitelson et al. 1993; He et al. 2008; Lavery and Pattiaratchi 1993).

The case study: the ACNA chemical factory

Studied area

The watershed of the Bormida River in the northwestern region of Italy covers about 2,600 km^2 including the watershed of the “Bormida di Millesimo”, the “Bormida di Spigno” and the main stretch of the Bormida River, from its source as far as its confluence with the Tanaro River 154 km downstream. It flows northbound through 69 municipalities in two regions with a resident population of about 210,000.

The watershed of the “Bormida di Millesimo” (Fig. 1) covers about 265 km^2 from its source located in the Ligurian Alps at ~800 m altitude as far as its confluence with the “Bormida di Spigno” 110 km downstream. All the tributaries of the “Bormida di Millesimo” are characterised by a very irregular seasonal flow, strongly reduced during the summer.

According to the 2006 Coordination of Information on the Environment (CORINE) Land Cover map (http://sia.eionet.europa.eu/CLC2006/), the land use upstream of the ACNA plant is mainly classified into two classes: 311 “broad-leaved forest” and 324 “transitional woodland/shrub”. The CORINE Land Cover provides comparable digital maps of land cover for much of the countries of Europe. The map of Italy is distributed by the National

Fig. 1 The "Bormida di Millesimo" watershed

Environmental Information System Network (available at the http://www.sinanet.isprambiente.it/Members/mais/Corine/). The vegetation classification was carried out using medium-resolution images (SPOT-4 and IRS LISS III).

The "Bormida di Millesimo" Valley is characterised by homogeneous orography and sun exposition. Moreover, a study of the soils along the river performed using X-ray diffraction did not find evidence of important differences in the mineralogical constituting phases (Marengo et al. 2006).

Annual rainfall of the region is about 700 mm and the average discharge of the "Bormida di Millesimo" is about 2 m^3/s. These are the mean values of the data collected during the years 2003–2007 by the meteorological and hydrometric station located in Gabutti, in the municipality of Camerana (44,2613° N–8,0929° E), at an altitude of 360 m a.s.l., a few kilometres downstream of the ACNA chemical plant (http://www.regione.piemonte.it/ambiente/aria/rilev/ariaday/annali/meteorologici).

Figure 2 shows the monthly averaged discharge and precipitation of the period 2003–2007.

Until 1892, agriculture was the main activity of the inhabitants in the region. In the same year, a dynamite factory was founded in Cengio (on the Millesimo

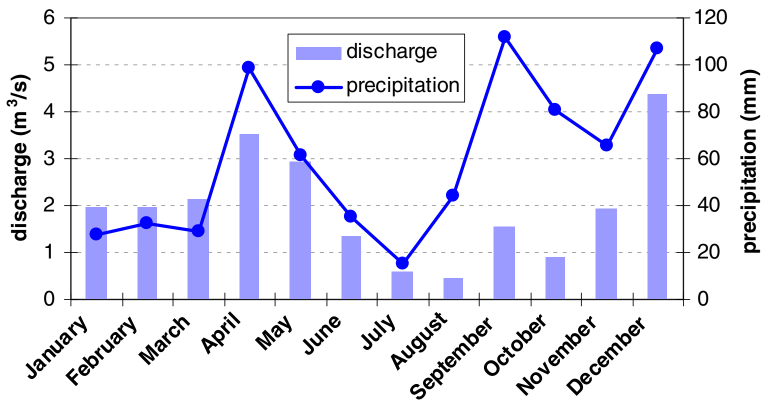

Fig. 2 Monthly averaged discharge and precipitation of the period 2003–2007 measured by the meteorological and hydrometric station located in Gabutti, a few kilometres downstream of the ACNA chemical plant

tributary), straddling the border between the Piemonte and Liguria regions. Within a few years, the workforce of the factory reached a total of 5,000, and the first environmental issues associated with the factory appeared.

In 1919, the factory output was converted to produce colouring agents for a wide variety of industries. This led to high levels of water pollution in the river and wells. Vegetables and grapes, irrigated using these waters, were reported to "smell of phenol" and, subsequently, local agriculture was abandoned. Epidemiological studies showed that a high percentage of deaths in the area were caused by bladder cancer, which was linked to contamination of irrigated locally grown fruits and vegetables (Bonassi et al. 1989; Puntoni et al. 1988). Concern by the local population over health risks of the polluted water resulted in growing unrest over the decades.

The entire area was declared a "high-risk area" in 1987 by the Italian Ministry of Environment. The factory was closed in 1998. A large load of carcinogenic substances, such as phenol and dioxin, were found in the soil beneath the factory. In 1999, a Special Commissioner was nominated to deal with the socio-environmental emergency within the area and to supervise environmental restoration of the site.

To explore the hydrological and environmental features of the Bormida River and to measure the extent of the environmental damage, national and local institutions carried out a systematic water quality monitoring programme (Ministero dell'Ambiente 2003; Ministero dell'Ambiente 2005). Soil and groundwater analysis of the site was initially performed to evaluate the degree and the extent of contamination for remediation purposes. Remediation activities lasted several years and included the implementation of emergency safety measures for basic intervention within the site, such as remediation of contaminated areas and disposing of saline wastewaters.

Several remediation goals had been completed by November 2006. Saline waste, accumulated within storage basins called lagoons inside the factory, had been treated and transported to its final destination, a salt mine in Germany. A containment system had been installed which performs several remediation functions. These include protecting the site from flooding and the removal of underground waters with subsequent channelling of percolate to the on-site water treatment plant. Remediation activities were facilitated outside the factory by removing industrial waste and contaminated soil. In 2008, contaminated soil was also found 3 km downstream the ACNA factory plant (Caiazzo and Viselli 2007; Hellmann 2005).

Satellite data

Three high spatial resolution multispectral images, acquired on 17 November 2003, 10 March 2006 and on 16 June 2007, were used. The images originated from the DigitalGlobe QuickBird satellite. This commercial remote sensing satellite stores data in four bands from visible to the near-infrared spectrum (1—blue, 450–520 nm; 2—green, 520–600 nm; 3—red, 630–690 nm; 4—NIR, 760–900 nm) of ~2.4-m nominal pixel spacing and a panchromatic band (450–900 nm) with a nominal pixel spacing of ~0.61 m (DigitalGlobe 2010).

These images detail a stretch of the Bormida River of about 20 km in length with a width of about 3.5 km. In Fig. 3, the satellite images are represented together with the path of the Bormida River with the regions of interest (ROIs, in red) selected for the analysis and the ACNA chemical factory (in yellow).

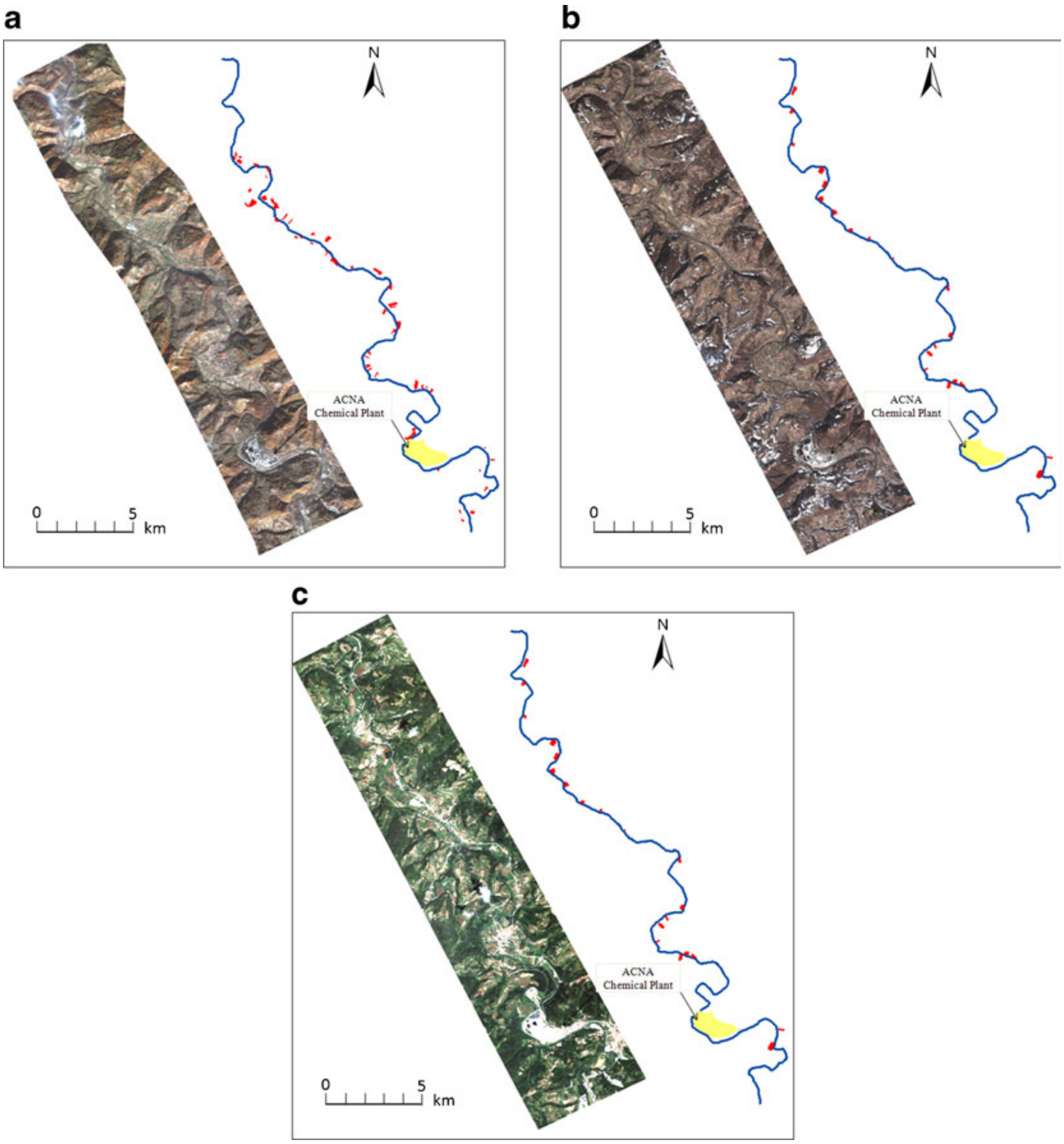

Fig. 3 True Colour (RGB) QuickBird images of the Bormida Valley. **a** 2003, **b** 2006, **c** 2007. © DigitalGlobe

Data analysis

The three images were analysed using the Environment for Visualizing Images 4.6 image processing system, a software package distributed by ITT Visual Information Solutions (ENVI 4.6 2008).

The atmospheric correction and at-the-ground reflectance calibration were operated by the FLAASH module of ITT ENVI. The parameters used in the atmospheric correction algorithm are summarised in Table 1.

In order to evaluate the changes during the years, we calculated the differences between the reflectance of the panchromatic portions of images containing the ACNA factory: 2003–2006, 2003–2007 and 2006–2007. Figure 4a–c shows the results in greyscale (arbitrary units). Light pixels indicate a reduction of reflectance, whilst dark pixels represent areas characterised by an increase in reflectance. Figure 4d represents the multi-temporal panchromatic image in True Colour (RGB), with the image of 17 November 2003 being red, the image of 10

Table 1 FLAASH atmospheric correction parameters

FLAASH parameters	2003	2006	2007
Sensor type	QuickBird 2	QuickBird 2	QuickBird 2
Pixel spacing (m)	2.4	2.4	2.4
Sensor altitude (km)	450	450	450
Flight date and time	17/11/2003 10:09:57	10/03/2006 10:39:53	16/06/2007 10:48:27
NW corner, Lat/Long	44.493° N, 8.095° E	44.494° N, 8.082° E	44.511° N, 8.078° E
SE corner, Lat/Long	44.343° N, 8.238° E	44.364° N, 8.219° E	44.346° N, 8.219° E
Ground elevation (km)	0.39	0.39	0.39
Visibility (km)	25	25	40
Atmospheric model	Mid-latitude winter	Mid-latitude winter	Mid-latitude summer
Aerosol model	Rural	Rural	Rural
Water vapour retrieval	–	–	–
Spectral polishing	No	No	No
Wavelength calibration	Yes	Yes	Yes
Advanced parameters	Common	Common	Common

March 2006 being green and the image of 16 June 2007 being blue. This kind of image allows a prompt detection of remediation activities because the absence of one or two colours indicates a variation during these 3 years. As an example, the lagoons (on the left) are present in 2003 and in 2006, but not in 2007 after the removal of liquid waste was completed. Moreover, the demolition of the industrial buildings is noticeable. The red dot indicates the origin of the axis representing the distance from ACNA factory.

In order to distinguish vegetated areas from bare soil, the Decision Tree classification method was applied. The Decision Tree classification method involves the classifier carrying out a multistage classification by taking a series of binary decisions to place the pixels into different classes (ENVI 4.6 2008). Four expressions, one for each band, were used as inputs. These expressions quantify the reflectance ranges from a vegetated area. The reflectance values of a known vegetated area were employed as a training dataset to perform the classification.

The area under study is covered by four CORINE classes: 242 including complex cultivation patterns, 243 including lands mainly occupied by agriculture with significant areas of natural vegetation, 311 including broad-leaved forest and 324 including transitional woodland and shrub. We selected only vegetated regions with similar characteristics, i.e. 242 and 243 CORINE classes.

High-resolution images make it possible to identify fields covered by different types of vegetation. To analyse comparable data, we choose only ROIs of agricultural fields along the banks of the Bormida River, both upstream and downstream of the ACNA factory site. For each image, the mean spectral signature of all the ROIs and the standard deviation were computed. The mean values of the ROIs in band 4 are very different from each other, whilst in bands 1, 2 and 3, the ROI mean values are more comparable. The ROIs having the mean values of 1, 2 and 3 bands out of the interval "mean value of all the ROIs±standard deviation" were rejected. Within the image of 2003, 34 fields were selected, 20 on the image of 2006 and 28 on the image of 2007. Each ROI contains more than 200 pixels, where a single pixel represents an area of 2.4×2.4 m. For each ROI, the median of the Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) values were computed.

Chemical index

Many survey campaigns have been carried out on the Bormida River Basin in recent years, with the aim of characterising the influence of pollution originating from the ACNA factory. To compare in situ measurements obtained in these survey campaigns with the NDVI and EVI values, we considered different soil samples collected on the riverbanks.

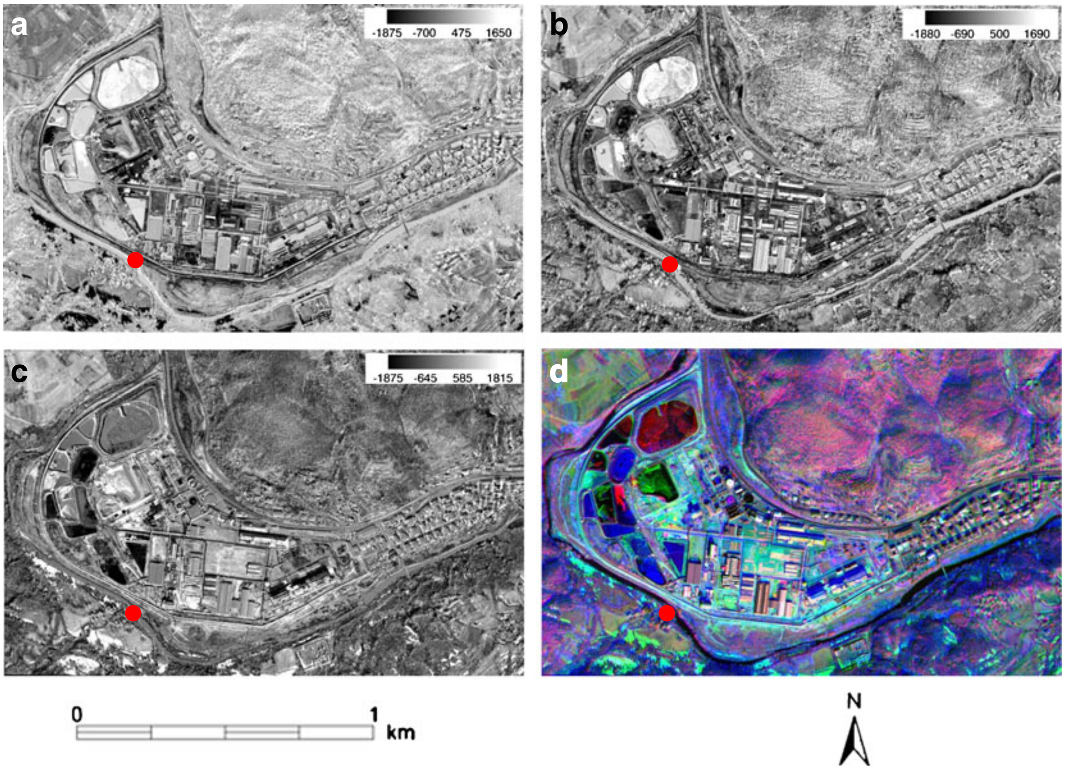

Fig. 4 Greyscale images of the panchromatic subtraction in the area of the ACNA chemical factory. **a** 2003–2006. **b** 2003–2007. **c** 2006–2007. **d** Multi-temporal panchromatic image in RGB colours of the ACNA chemical factory: 2003 (*red*), 2006 (*green*), 2007 (*blue*). The *red points* indicate the starting positions of measurements along the Bormida River

The amount of contaminants detected in the studied area during a 2002 sampling campaign is reported in Table 2. The content of metal contaminants was determined with the inductively coupled plasma mass spectrometry technique using an X5 ThermoElemental (Winsford, UK) after calibration with certified standards.

It is possible to assess the pollution level by the concentration values of individual chemical substances within the soil. However, when several toxic substances co-occur, the collective toxicity of the substances has to be assessed. For this purpose, we evaluated the chemical index (CI) proposed by Trivero et al. (2007) and defined by the following equation:

$$CI = \prod_{x_i > x_{0i}} e^{-\frac{x_i - x_{0i}}{x_{0i}}} \qquad (1)$$

where x_i is the actual measured concentration value of the different metal ions that Marengo et al. (2006) obtained by analysing soil samples on the riverbanks and x_{0i} is the Italian standard for concentrations in agricultural soils, as summarised in Table 3. Only pollutants with concentrations greater than the thresholds are considered in Eq. 3. CI values ranged between 0 and 1, with higher CI values corresponding to lower levels of pollution. The CI values summarised the toxic effects of the metal ions considered. These were chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb). The CI values have been calculated for the samples reported in Table 2.

Vegetation indexes

In recent years, several studies have been published, pointing out the usefulness of the NDVI for assessing the environmental impacts of pollution (Fravretto et al. 2003; Virtanen et al. 2002; Zorzi et al. 2005). The NDVI has been also widely used to assess recovery processes as it is sensitive to changes in the fractional vegetation cover until a full cover is reached (Carlson and Ripley 1997). Vegetation indices like the NDVI and the EVI are widely used to monitor seasonal, inter-annual and long-term variations of structural,

Table 2 Contaminants and their concentrations (in milligrams per kilogram) in different samples collected in the riverbanks along the Bormida River

Sample	DIST_ACNA	DIST_ALVEO	Cr	Ni	Cu	Zn	As	Cd	Hg	Pb
AL21	−1995	104	176	142	22.1	83.3	35.3	0.48	0.25	32.3
AL1	−1925	104	123	43.9	29.8	105	43.9	0.57	0.09	61.4
AL2	−933	55	62.5	28.1	16.2	78.1	32.8	0.32	0.09	43.2
AL22	1371	81	204	81.6	30.6	102	51.0	0.40	0.39	43.9
AL13	3322	60	235	58.8	43.1	113	58.8	0.40	0.12	58.8
AL24	4050	248	392	231	47.2	80.2	19.3	0.47	0.09	25.5
AL7	4810	48	202	90.9	26.3	116	26.3	0.50	0.76	43.4
AL15	8606	22	240	130	40.1	88.5	30.7	1.15	0.21	45.3
AL9	14827	59	314	144	44.2	133	35.6	0.40	0.09	33.5
AL16	17636	32	188	101	19.7	48.1	35.1	0.40	0.25	14.9

DIST_ACNA indicates the distance (in metres) from the ACNA plant and DIST_ALVEO the distance (in metres) from the Bormida River. Negative values refer to samples located upstream of the ACNA plant

phenological and biophysical parameters of vegetation cover (Barbosa et al. 2006; Huete and Liu. 1994; Huete et al. 2002; Jiang et al. 2006; Orshan 1989).

Vegetation indices are usually calculated using a combination of two or more bands, in particular red (R), near-infrared (NIR) and blue (B) channels.

The NDVI is defined by the following equation:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{2}$$

where R and NIR stand for the atmospherically corrected spectral reflectance measured in the red and near-infrared regions, respectively. NDVI values range between −1 and +1.

The NDVI is a good descriptor of vegetation in particular because the normalization process minimises both the atmospheric effects and the radiometric degradation in the red and infrared bands (Santos et al. 1999). Whereas the NDVI is chlorophyll-sensitive, the EVI is more responsive to canopy structural variations, including the leaf area index, canopy type, plant physiognomy and canopy architecture (Gao et al. 2000).

The EVI is defined by the following equation (Huete et al. 1994):

$$EVI = G\frac{NIR - R}{NIR + C_1 R - C_2 B + L} \tag{3}$$

where NIR, R and B stand for the atmospherically corrected surface reflectance measured in the near-infrared, red and blue regions, respectively, G is a gain factor, L is the canopy background adjustment, and C_1 and C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in the EVI algorithm are L=1, C_1=6, C_2=7.5 and G=2.5 (Huete et al. 2002).

The EVI was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmosphere influences (Huete et al. 2002, 2006; Jiang et al. 2008).

Table 3 Toxic concentration standards for metals in soil

	Chromium (Cr)	Nickel (Ni)	Copper (Cu)	Zinc (Zn)	Arsenic (As)	Cadmium (Cd)	Mercury (Hg)	Lead (Pb)
Toxic threshold (mg kg^{-1})	150	120	120	150	20	2	1	100

Discussion and results

We used remote sensing high-resolution images to monitor and compare, over several years, the vegetation along the river course in proximity to the ACNA chemical factory and in the contiguous area. We computed the NDVI and the EVI to assess the vegetation conditions along the water course. Environmental stressors, such as toxic metals, produce alterations in the biochemistry and cellular composition, resulting in the reflectance change of different bands that are detected by remote sensors (Asner 2004). Those results have been utilised to evaluate the results of remediation actions applied in the region. The trends of NDVI and EVI values, calculated for the three images, are represented in Fig. 5. The abscissa origin represents the ACNA factory position (see Fig. 4). The upstream and downstream distances from the factory are measured along the course of the river.

In Fig. 5, all the NDVI and EVI values were higher in the image acquired in 2007 than those calculated for the 2006 and 2003 images. This feature is due to the relation between the vegetation indices and phenological cycle of vegetation because of the different seasonal and meteorological conditions of acquisition among the images. In fact, the 2007 image was acquired in June: generally, this month, for annual vegetation, corresponds to the peak of biomass, the most productive phase of the phenological cycle. The image acquired in March, during the pre-peak phase, is characterised by the presence of sparse and younger vegetation or minor green biomass. The image acquired in November, during the post-peak phase, is characterised by a minor biomass with withered plants (or part of plants).

Whilst seasonal differences between the three images could potentially make a reliable comparison between the NDVI and EVI absolute values problematic, in this case, we compare the NDVI and EVI trends, and not the absolute values, in the three images. This can be done because the investigated stretch of the river shows no changes in either climate or in the soil composition during the same season (see paragraph 2).

In all the images, the NDVI and EVI values were higher in the stretch upstream of the factory, showing a relatively unaltered ecosystem compared with downstream. The NDVI and EVI values generally showed significant fluctuations, but their trends decreased drastically throughout the ACNA chemical factory site, increasing again in the downstream stretch of the river and reaching the higher seasonal values typical of unimpacted conditions about 16 km downstream. Within the image of 2007, the NDVI and EVI values showed a rapid increase, with higher values reached at Saliceto. Within the graphs shown in Fig. 5, the regression lines in the interval from 6 to 17 km are also represented, showing the same slope in 2003 and 2006, whilst in 2007 the regression line is horizontal. Even taking into account the fluctuations of the values along the river, the trend of the improvement due to the remediation action is evident. However, it is worth noting that pollutants were found in the area near the ACNA factory, also after 2007.

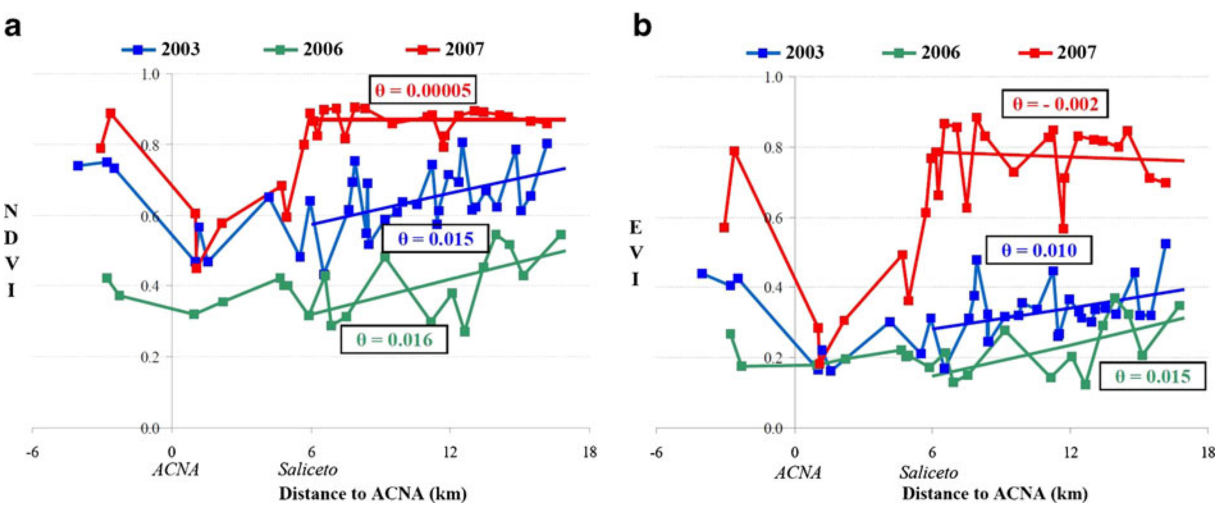

Fig. 5 NDVI (**a**) and EVI (**b**) values of ROIs along the Bormida River and regression lines from 6 to 17 km. θ represents the slope value

The rapid decrease of both NDVI and EVI across the ACNA factory site can be correlated with the load of pollutants released into the river. The effects of this pollution are noticeable in a long section of Bormida Valley downstream of the ACNA factory site. The contamination produced by the ACNA factory had less severe effects in 2007 than in 2003 and 2006, with the pollution effect limited to only 6 km beyond the ACNA factory site in 2007. This result indicates the effectiveness of remediation activities carried out in the area.

The comparison between NDVI and EVI confirms that the NDVI tends to rapidly saturate with respect to the EVI, reducing its sensitivity for monitoring and assessing spatial and temporal variations in vegetation condition (Huete et al. 2002). In order to validate the proposed methodology with in situ measurements, we first took into account data from the soil sampling campaign described in Marengo et al. (2006). This dataset is particularly useful because samples have been collected along the river at different distances from the ACNA plant and, therefore, a spatial trend can be plotted.

We evaluated the CI for a subset of sampling points in the same river stretch where EVI was available, and then we plotted its spatial trend versus the distance from ACNA. To compare NDVI and EVI with chemical data, we applied a Hamming filter (Hamming 1989) to the obtained CI plot in order to smooth the fluctuations and evidence the trend instead. Being a low-pass filter, the Hamming filter is suitable for this purpose and is often used for noise reduction applications. The result is shown in Fig. 6.

The CI pattern is comparable with the NDVI and EVI trends of the years 2003 and 2006. In Fig. 7, the correlation between the CI and the EVI of the year 2003 is represented. Although the CI and EVI values were computed for different fields and despite the small number of points, it is possible to observe a relationship among the values of the two indices.

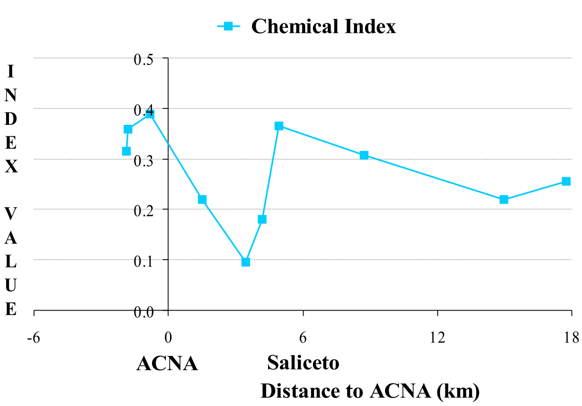

Fig. 6 Chemical index trend along the Bormida River

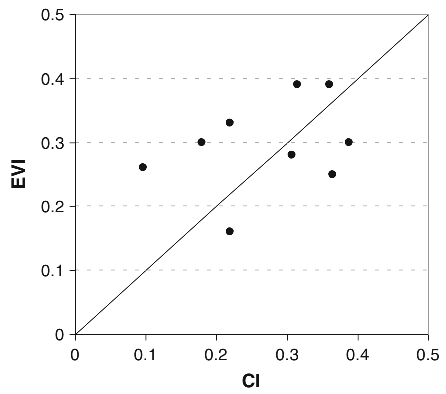

Fig. 7 Scatterplot between the chemical index and 2003 EVI values

A further validation of our results can be found in Avidano et al. (2005), where a similar chemical sampling campaign is described. Here, only two soil samples are acquired close to the plant, at −0.5 km and at + 0.5 km according to the abscissae of Fig. 5: the values are shown in Table 4. Although only two points are available, it is possible to observe how pollutants' concentrations are much higher in the second point, according to the EVI trend. Moreover, the first point shows the presence of pollutants in amounts less than the standards, being classified as "clean".

These in situ measurements confirm the suitability of satellite images, and derived indices, as useful tools for vegetation monitoring. This methodology is nowadays widely applied: our work can be compared with other similar approaches were optical and infrared satellite data have been used to monitor vegetation

Table 4 Quantitative evaluation of chemical pollutants in each soil site compared to the guideline value (in milligrams per kilogram)

Distance	Pollutants	Concentration	Guideline value
−0.5 km	Arsenic	24	50
	Mercury	4.2	5
	Tetrachlorobenzene	9.1	25
	2,4-Dichloroaniline	2.4	5
+0.5 km	Total copper	790	600
	Arsenic	180	50

changes, such as the recovery of forests after burning (Ramsey et al. 2002), as well as the deterioration of vegetation due to industrial pollution (Virtanen et al. 2002; Rastmanesh et al. 2010).

Evaluations are usually carried out by computing NDVI on selected areas from medium-resolution satellite images (Landsat TM/ETM in the cited examples). With respect to this approach, we pointed out the possibility to evaluate spatial trends in addition to temporal evolution. We also evidenced the advantages of higher resolution images available nowadays.

Conclusions

Environmental effects of water pollution were assessed by means of NDVI and EVI values calculated for homogeneous fields along the Bormida River. Thanks to the high spatial resolution of the satellite sensors, NDVI and EVI can be applied for monitoring riverbanks, even within small areas. Moreover, the high resolution allows an estimation of the terrain covered by vegetation and therefore makes a more detailed evaluation of the health status of the vegetation possible.

The EVI demonstrated a better dynamic range and sensitivity for monitoring and assessing spatial and temporal variations in vegetation condition with respect to the NDVI. The trends of the EVI prior to the completion of remediation are generally supported by chemical analyses of toxic metals measured in soil samples.

In conclusion, the NDVI and EVI obtained from high-resolution satellite images show their usefulness as additional tools to assess vegetation health and then can be used as suitable survey tools for fluvial environment studies.

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