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Review

Which lesson can be learnt from a historical contamination analysis of the most polluted river in Europe?

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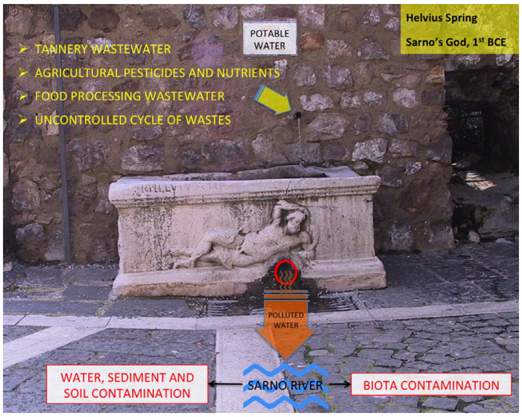
HIGHLIGHTS

- Sarno River is far from reaching the 2015 goal of Water Framework Directive.
- A full knowledge of the health status of Sarno River was provided.
- Poor wastewater management and agricultural pressures as main weaknesses
- Restoration of vital flow and river contracts as immediate and low cost solutions

GRAPHICAL ABSTRACT



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ABSTRACT

The Sarno River trend analysis during the last 60 years was traced focusing on the socio-economic and environmental issues. The river, originally worshiped as a god by Romans, is affected by an extreme level of environmental degradation, being sadly reputed as the most polluted river in Europe. This is the "not to be followed" example of the worst way a European river can be managed. Data about water, sediment, soil, biota and air contamination were collected from scientific papers, monitoring surveys, and technical reports depicting a sick river. Originally, the river was reputed as a source of livelihood, now it is considered a direct threat for human health. Wastewater can still flow through the river partially or completely untreated, waste production associated with the manufacture of metal products and leather tanning continues to suffer from the historical inadequacy of regional wastewater treatment plants (WWTPs), associated with the partial or no reuse of effluents. All efforts should be devoted to solving the lack of wastewater and waste management, the gap in land planning, improving the capacity of existing WWTPs also via the construction of new sewer sections, restoring Sarno River minimum vital-flow, keeping to a minimum uncontrolled discharges as well as supporting river

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contracts. The 2015 goal stated by the Water Framework Directive (2000/60/EC) is still far to be reached. The lesson has not been learnt yet.

Contents

1. Introduction

When considering the state of rivers, a long history emerges in association with urban ecology, disposal of wastewater and societal and cultural traditions (Libralato et al., 2010a, 2010b; Lofrano and Brown, 2010; Vita-Finzi, 2012; Pinto and Maheshwari, 2014). Decreasing precipitation and (mis-)management combined with administrative and structural constraints, poor environmental planning and inspection and, frequently, a lack of environmental awareness imposed significant pressures on rivers (Skoulikidis, 2009). For a long time, according to the principle "*the solution to pollution is dilution*", dispersion has been the dominant strategy for wastewater management, but not the best habit. Unfortunately, it continues to be practiced in many developed and developing countries (Libralato et al., 2009, 2012; Lofrano and Brown, 2010). The self-depurative capacity of water bodies enabled tolerating the discharge of natural and synthetic chemicals for centuries. Nowadays, water bodies must be protected preventing further degradation of their environmental quality, being the self-depurative capacity compromised by prolonged massive discharges, as in the case of the River Thames (London, UK) (Halliday, 1999; Arienzo et al., 2001; Vita-Finzi, 2012).

The complex network of interactions that binds surface water and groundwater suggests that poor river quality can affect human health and the environment due to the presence of substances and microorganisms with potentially (eco-)toxic effects, thereby leading also to biodiversity loss (Motta et al., 2008; Montuori et al., 2013; Albanese et al., 2013a, 2013b, 2015). Despite strong fragmentation, most rivers are liable to flash floods and low summer flow (Skoulikidis, 2009). Generally, lowland river sections are hydro-morphologically modified, presenting the highest risk of contamination, while upstream areas mostly retain their natural conditions. International treaties and European Union (EU) directives, such as the Water Framework Directive (WFD, 2006/60/EC), have highlighted the urgent need for integrated river basin management. Nevertheless, the WFD aimed to achieve a 'good chemical and ecological quality status' of water bodies by 2015, and its application was occasionally disregarded, with no actions being taken at the local or regional scales (IMPRESS, 2002).

The Sarno River plain (40° 46′ 1.12″ N, 14° 33′ 46.04″ E) in the Campania Region (Italy) is the chief example of how uncontrolled development can affect the future of a land (De Pippo et al., 2006; Albanese et al., 2015). The Sarno flatland is one of the most fertile flatlands in Italy due to the high agronomic quality of its soil, constituted by layers of volcanic and alluvial origins, the presence of water and the favourable climatic conditions (Loiudice et al., 1995; Allevato et al., 2012; Albanese et al., 2013a). In the upper part of the Sarno River basin, tannery has been favoured by pastoralism and freshwater availability since pre-historic times; the third Italian leather tannery district (*Solofra* town) is still located in this area (UNIC, 2013).

In the Sarno basin, human activities have significantly impacted the riverine ecosystem and the water quality of the Gulf of Naples. The first attempt of Sarno River decontamination was in 1973 with the Special Project 3 (SP3) sponsored by *Cassa del Mezzogiorno*, a public body that was created to support the development of southern Italy. The purpose of this attempt was to restore good environmental conditions in the Gulf of Naples after a violent cholera epidemic; this restoration was primarily achieved through wastewater management. Thus, wastewater treatment plants (WWTPs) and the relative wastewater collection system were built. After approximately 40 years and 700 Million €, wastewater is still of great concern (Parliamentary Commission of Inquiry, 2006).

Currently, few scientific papers exist regarding the Sarno River. These studies have investigated environmental riverine issues (Arienzo et al., 2001), as well as the neighbouring lands (Adamo et al., 2003), discussing hydrogeological conditions (De Pippo et al., 2008) or health risks that are associated with living near this river (Motta et al., 2008; Vigliotta et al., 2010). A comprehensive evaluation of environmental criticisms, their origin and future trends on this "not-to-be followed" example of the worst way a European river can be managed is currently missing.

The authors assessed the river catchment development in the last 60 years (1951–2014), considering socio-economic and environmental issues, collecting information from scientific papers, public datasets, and technical monitoring reports, highlighting an extreme case of environmental problems within the EU. The impacts of a range of environmental pressures were described in detail along with the responses of the competent authorities. The data were analysed and presented i) to consider increasing and historical difficulties in improving Sarno River general quality, ii) to deliver its current state and basic information in the perspective of approaching WFD objectives, even if already failed under a time-based viewpoint, and iii) to discuss the remaining environmental challenges.

2. Methodological approach and data collection

The Driver-Pressure-State-Impact-Response (DPSIR) framework (EC, 2003; Borja et al., 2006; EC, 2008) was used to evaluate (i) the socio-economic factors (D, Drivers) forcing anthropogenic activities (P, Pressures), (ii) the resulting environmental conditions (S, State — e.g., concentration of pollutants and disturbance of hydrological regime), (iii) the main consequences (I, Impacts — e.g., eutrophication, fish death and non-potable water) and (iv) the measures taken to improve the current environmental state (R, Response).

Sarno catchment basin maps were generated using QGIS Open source software (QGIS Development Team, 2015) intersecting a series of constructed basic and derived thematic records. The collection and analysis process involved the acquisition of spatial and historical water quality data between 1951 and 2014. The observation period began in 1951 when Italy started its modernisation process after World War II.

The Italian National Institute of Statistics (ISTAT) provided the administrative records about Sarno municipalities and industries (ISTAT, 1951, 1961, 1971, 1981, 1991, 2001 and 2011). Data on Sarno environmental quality were acquired from scientific publications (Arienzo et al., 2001; Montuori and Triassi, 2012; Montuori et al., 2013) and monitoring reports that were produced by the Campania Region Environmental Protection Agency (ARPAC, 2003–2012) and a non-governmental organization (Legambiente, 2014).

3. Sarno catchment basin features

3.1. General river framing

The study area falls within the temperate Mediterranean climatic belt (17.6 °C — annual mean), characterized by frequent, often localized and intense rainfall (1085 mm — annual mean), which is mostly concentrated in November. Conditions become stormy in the presence of persistent high humidity that is generated by the dense network of land reclamation and irrigation canals crossing the flatland and the air masses approaching from the sea.

The hydrographic basin of Sarno River (Fig. 1) is bounded to the north by *Somma-Vesuvius* volcanic complex, eastward by the Sarno massif (*Mts. Picentini*), southward by the carbonate reliefs of Sorrento Peninsula (*Mts. Lattari*) and westward by the Bay of Naples. This area covers approximately 483 km^2 (i.e., approximately 5% of the Campania Region), including 3 provinces (*Avellino*, 17%; *Naples*, 29%; and *Salerno*, 54%) and 38 municipalities (Fig. 2) that are grouped into three primary administrative districts (Upper, Middle and Lower Sarno).

All of the reliefs surrounding the Sarno flatland, except for *Somma-Vesuvius* volcanic complex, are made of carbonates. Carbonate rocks are covered with layers of pyroclastic deposits gradually decreasing from the plain to the inside of the relief chain. The plain includes an extensive subsiding tectonic depression that was established between the end of Pliocene and the beginning of Pleistocene due to the major tectonic uplift events of the lower and middle Pleistocene along the margins of *Apennines* chain (Cinque et al., 1987; Vogel and Märker, 2010). Quaternary deposits are present and consist primarily of pyroclastic and alluvial depositions on carbonate bedrock that is equally fractured due to the tectonic activity of the complex *Somma-Vesuvius*, as well as altered by the action of water run-off (Parliamentary Commission of Inquiry, 2006). The geological and geomorphological features favour the occurrence of landslides involving spatially continuous surface and deep deformations.

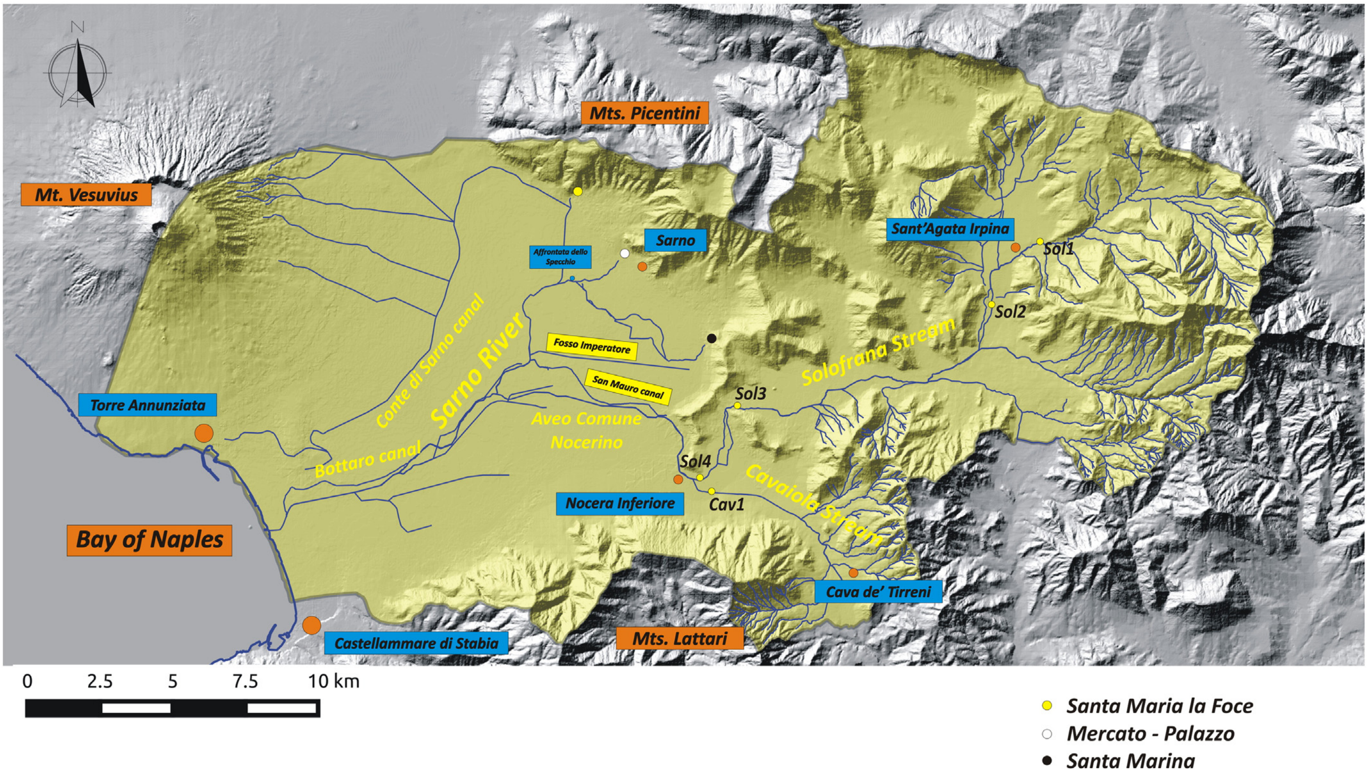

Fig. 1. The hydrographic basin of Sarno River; SOL1-4 = Solofrana stream sampling points, CAV1 = Cavaiola stream sampling point.

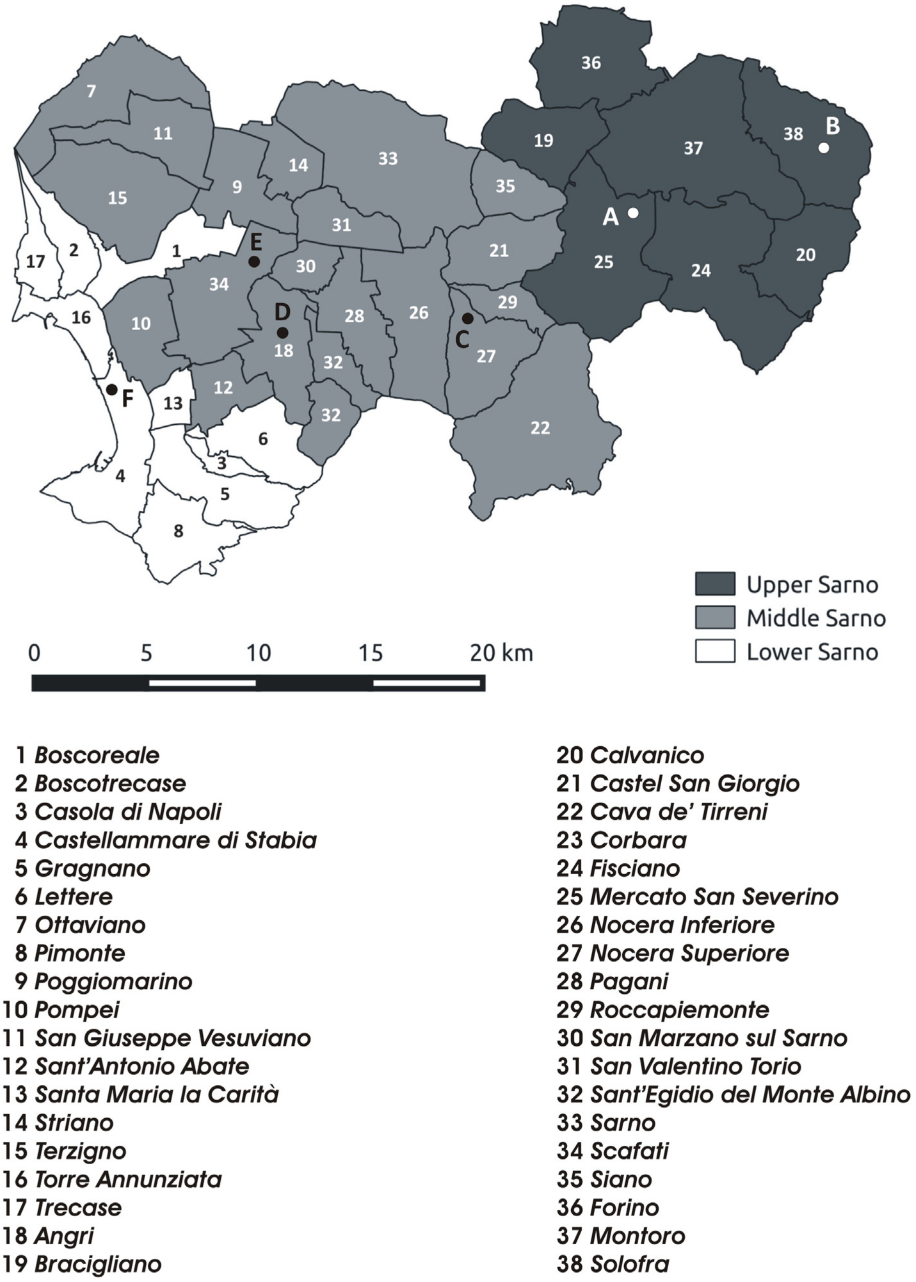

Fig. 2. The 38 municipalities in the Sarno River basin are clustered in three districts: Upper Sarno, Middle Sarno and Lower Sarno. Circles show the location of the six wastewater treatment plants: (A) Mercato San Severino, B) Solofra, C) Nocera, D) Angri, E) Sant'Antonio Abate/Scafati and F) Castellammare di Stabia.

The main groundwater flow occurs in two overlapping levels interacting with several minor shallow aquifers that are separated by a grey tuff bank. The shallow aquifer is mainly fed by rainwater, while the deep one is fed by underground water that is stored in the adjacent carbonate bedrock (Parliamentary Commission of Inquiry, 2006), hosting an aquifer that is more permeable than the flatland one. The Sarno River rises from the slopes of *Mount Saro* and is approximately 24 km long, debouching into the Bay of Naples (61 $m^3 s^{-1}$) between the municipalities of *Torre Annunziata* (NW) and *Castellammare di Stabia* (SE) (Fig. 1). The *Alveo Comune Nocerino* stream, which originated by the confluence of *Solofrana* and *Cavaiola*, is the main Sarno tributary (Arienzo et al., 2001; De Pippo et al., 2006). The *Solofrana* stream rises at the confluence of *Vallone Spirito Santo* and *Vallone de' Grani* in *Sant'Agata Irpina* flowing for 25 km in a catchment of approximately 135 km^2. The *Cavaiola* stream rises in the town of *Cava de' Tirreni* flowing in a concrete canal on a fixed course for 8 km in a catchment of approximately 87 km^2 (ARPAC, 2011). The Sarno hydrographic basin hosts several secondary tributaries that are approximately 1630 km long. Other contributions to Sarno River flow come from direct rainwater and groundwater flow from aquifers belonging to the limestone massifs outside of the basin area (ARPAC, 2014). The hydrographic network of the basin can be divided into three main sections: i) *Sarno River upstream the confluence of Alveo Comune Nocerino* (Fig. 1) — the initial tributary is fed by three springs 30 m above the mean sea level (*S. Maria della Foce*, *Mercato-Palazzo*, and *S. Marina di Lavorate*) forming the streams *Rio Foce*, *Acqua di Palazzo* and *Acqua di Santa Marina*. Their convergence gives rise to the main watercourse at *Affrontata dello Specchio*; ii) *Sarno River downstream the confluence of Alveo Comune Nocerino* (Fig. 1) — from the confluence of *Alveo Comune Nocerino*, the river bed was modified by several hydraulic works managing the water flow and slope (i.e., high ground or concrete banks); and iii) *Alveo Comune Nocerino*, *Solofrana and Cavaiola* (Fig. 1) — the third section of the Sarno hydrographic network originates from the confluence of *Cavaiola* and *Solofrana* into the *Alveo Comune Nocerino* at *Nocera Inferiore*. In addition, two major canals, *Conte di Sarno* (*S. Maria la Foce* spring) and *Bottaro* (*Scafati* spring), are connected to the Sarno River. Both of these canals are primarily used for irrigation and partly for industrial purposes.

3.2. Historical background

Over the centuries, the Sarno riverbed has had numerous detours and changes caused by natural and sometimes catastrophic events. Since the Neolithic Age, the Sarno area has been inhabited, and various anthropogenic and natural pressures have alternated and stratified as summarised in Fig. 3. The flatland was transformed into a huge garden, but the eruption of Vesuvius (79 AD) turned it off for a long time until its revitalization thanks to the re-emergence of the river (Vogel and Märker, 2010). Since the 16th Century, human intervention has resulted in bulkheads, water withdrawals to support intensive agriculture and industry, watercourse coating and riverbed sections' transformation into highways (Parliamentary Commission of Inquiry, 2006; Allevato et al., 2012). On 5 May 1998, the town of *Sarno* and the neighbouring villages were devastated by a series of catastrophic landslides killing 160 people. These landslides originated by a combination of heavy rainfall events and land overexploitation (i.e., agricultural, residential and industrial pressures) in association with the absence of any land planning. Today, approximately 180 km of the Sarno River hydrologic network is roads, and 98 km is completely covered, highlighting that 17% of the entire river has been profoundly changed. As a result, flooding events increased in frequency, and water stagnated, making the surroundings unhealthy. Then, the river was further modified due to the increase in residential and industrial pressures worsening its water quality and the general living conditions of the inhabitants (De Pippo et al., 2006; Motta et al., 2008).

4. Drivers

4.1. Demography

In Fig. 4, the population growth rate (%) for the 3 Sarno River basin districts was compared to that of Sarno catchment, Campania Region and Italy from 1951 to 2011. Since the end of the Second World War, the flatland has experienced a rapid and uncontrolled urban development. Within the 38 municipalities that are included in its basin, the population increased by 42%, presenting a maximum growth rate of 19% in the first two decades (1951–1971). In the Middle Sarno area, the population increased by more than two times (54%) the national average (20%). In the Upper Sarno area, the highest growth rate occurred from 1971 to 1991, coinciding with the spread of the leather tanning industry, such as in Solofra town (29%). The population increased in Lower Sarno to higher (25%) than the national level (20%) (Fig. 4) but still lower compared to that of the other districts (33% in Upper Sarno and 54% in Middle Sarno). As shown in Table 1, in Lower Sarno, 1853 inhabitants km^{-2} (1951) increased to 2376 inhabitants km^{-2} in 30 years (ISTAT, 1951, 1961, 1971, 1981, 1991, 2001, 2011). In particular, in 1981, the town of *Torre Annunziata* housed 8258 inhabitants km^{-2}, which was more than Singapore (7681 inhabitants km^{-2}) and London (UK) (2550 inhabitants km^{-2} in 2011) (UK ONS, 2011).

From the last Italian census (ISTAT, 2011), the number of inhabitants per house was 2.89, 3.03 and 3.01 in Upper, Middle and Lower Sarno, respectively, being notably close to the average value of the Campania Region (2.85 inhabitants per house). Although there is no overcrowding at the district or basin level, there is one-half inhabitant per house more than the national mean (2.46 inhabitants per house). This area is characterized by 444 houses km^{-2}, which is approximately three and five times higher than the regional (149 house km^{-2}) and national (80 house km^{-2}) averages, respectively.

4.2. Agricultural land use

Agriculture is one of the main activities of flatland, mainly consisting of open field and greenhouse horticulture, orchards and floriculture.

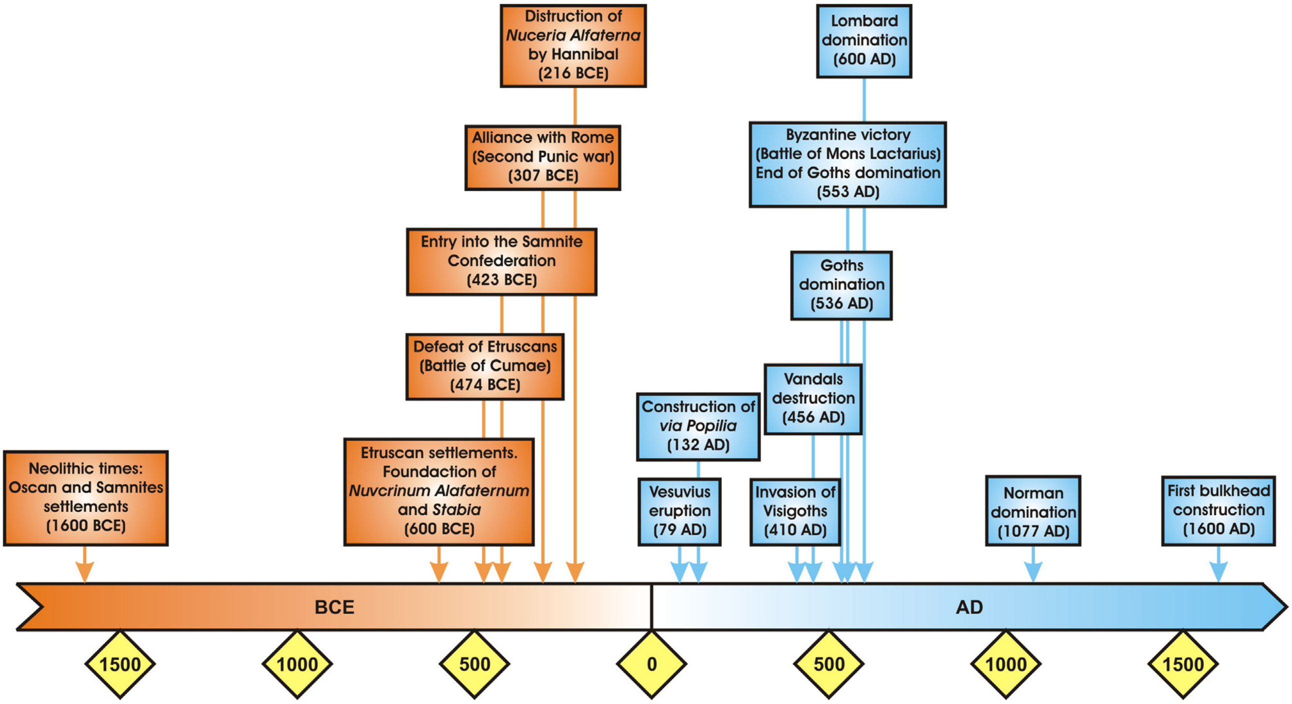

Fig. 3. Timeline of the main historical events occurred in the Sarno flatland between 1500 BCE and 1500 AD.

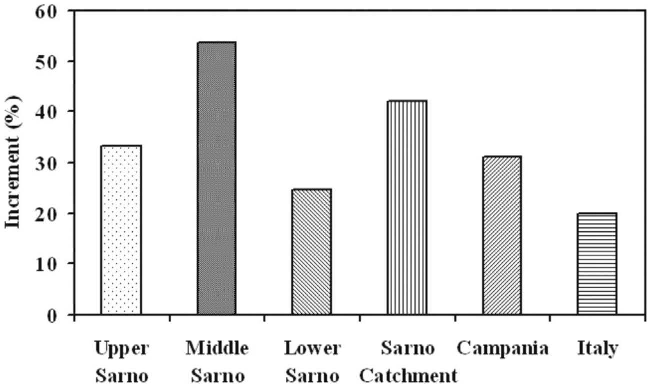

Fig. 4. The population growth rates (%) in Sarno River basin districts compared with Sarno catchment, Campania Region and Italy values for the same period (1951–2011) (data from ISTAT, 1951, 1961, 1971, 1981, 1991, 2001, 2011).

On the southern slopes, the landscape consists mainly of terraces where horticulture, fruit trees and vineyards coexist, while chestnuts are widespread on the north-facing slopes. Tomatoes (*Lycopersicum lycopersicum* L., *San Marzano*) are the principal crop, covering more than 3500 ha (Montuori and Triassi, 2012). However, as shown in Fig. 5, the space for agriculture decreased between 1982 and 2010 by approximately 64%, suggesting that most agricultural land was either abandoned or used primarily for commercial or industrial activities.

As a consequence, the number of farms decreased from 33,727 in 1982 to less than 7300 in 2010 within the entire Sarno basin (ISTAT, 2010).

4.3. Industrial development

In addition to leather tannery, the area is characterized by the presence of other industrial activities that are distributed within the three districts as shown in Table 2. The most important industries operate within agri-food and metal, clothing and leather manufacturing. The agri-food industry developed between 1971 and 1991 before undergoing a substantial decline between 2001 and 2011 (ISTAT, 1951, 1991). Metal manufacturing represents (Middle Sarno) the main economic sector after the agri-food industry (Table 2). The leather tannery industry increased between 1971 and 2001, mainly in Upper Sarno (89.7%), decreasing by approximately 25% in the last decade (ISTAT, 1951, 1971, 1991, 2001, 2011). Currently, less than 400 industrial activities remain, employing approximately 2700 workers. The pharmaceutical industry hosts 9 industrial plants, including Novartis Pharma, which covers 201,000 m^2 at approximately 200 m from the river outlet (Tornero and Ribera d'Alcalà, 2014).

5. Environmental pressures

Pressures originating from urban density, as well as from agricultural and industrial activities, cause great environmental concern in the Sarno catchment basin. These activities consume high amounts of water, generating point and non-point sources of nutrients, trace metals, and other inorganic (Table 3) and organic contaminants (Table 4), as well as solid wastes.

Table 1
Population density in the Sarno's catchment (inhabitants km^{-2}).
Data from ISTAT, 1951, 1961, 1971, 1981, 1991, 2001, 2011.

Sarno districts	1951	1961	1971	1981	1991	2001	2011
Upper Sarno	282	287	277	313	352	378	411
Middle Sarno	916	1046	1129	1237	1355	1399	1465
Lower Sarno	1853	2056	2142	2376	2366	2311	2266

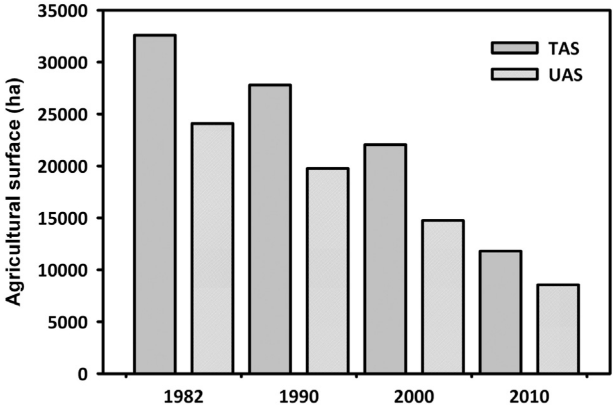

Fig. 5. Comparison between Total Agricultural Surface (TAS) and Used Agricultural Surface (UAS) in Sarno River basin in 1982, 1990, 2000 and 2010.
Data from ISTAT, 1982, 1990, 2000, 2010.

5.1. Water consumption and wastewater

It is well known that agriculture generates pressures on the environment, consuming 70% of the global freshwater and releasing high amounts of pollutants (UNESCO-WWAP, 2009). The Sarno River is broadly used both as a source of irrigation water and a way to discharge wastewater. For example, the *Conte Sarno* canal is used to drain water from one of the river's springs to irrigate the neighbouring lands. Agricultural activities have affected the Sarno River with fertilizers, pesticides and other wastes (Arienzo et al., 2001) as mentioned in Tables 3 and 4. In 2010, the flatland was sprayed with approximately 251.1 t of herbicides, insecticides and fungicides (ISTAT, 2010). Globally, agri-food production is amongst the top three activities responsible for the overall environmental pressures, along with mobility (e.g., automobile and air transport) and housing (Tukker et al., 2006; UNEP, 2010). Although studies on the environmental pressures of agricultural products are now frequent, those on processed industrial products remain scarce. These data would be very useful because the EU regulation of food product environmental impact is still forming.

Metal product manufacturing is a source of high-strength wastewater containing heavy metals, inorganic salts and a large amount of several xenobiotic compounds. The wastewater from these plants is often treated on site before river discharge. Although the clothing manufacturing industry is the third economic sector of the basin, it exerts a low local environmental pressure because most raw materials are produced and imported from foreign countries (Tornero and Ribera d'Alcalà, 2014). In contrast, the pressure from the leather tanning industry is a current and increasing problem (Lofrano et al., 2013). Water consumption varies greatly between tanneries, depending on the processes that are involved, the raw material that is used and the manufactured products (Lofrano et al., 2008). A large amount of freshwater is used along with many potentially dangerous chemicals, such as chromium, synthetic tannins, oils, resins, biocides and detergents (Lofrano et al., 2013). The effluents that originate from this industry are of great concern due to the potential toxic effects that are caused by the mixture of compounds that are used in the manufacturing process that can be released into the environment even after conventional activated sludge treatments (Jochimsen and Jekel, 1997; Meriç et al., 2005; Oral et al., 2007; De Nicola et al., 2007; Libralato et al., 2011).

Wastewater collection and treatment systems have been historically inadequate throughout the Sarno area (Parliamentary Commission of Inquiry, 2006). Half of the 38 municipalities collect less than 33% of the wastewater, and 7 municipalities collect between 33% and 66%. Only 13 municipalities have a sewage system collecting more than 66% of the wastewater. The industrial organic load, as estimated

Table 2
Distribution of manufacturing industries in various economic sectors.
Data from ISTAT 2011.

Economic sector	Numbers of manufacturing industries for every economic sector and district				Distribution of every economic sector in the three different districts (%)			
	Upper Sarno	Middle Sarno	Lower Sarno	Total	Upper Sarno	Middle Sarno	Lower Sarno	Total
Agri-food industries	85	642	257	984	8.64	65.24	26.12	100.00
Metal manufacturing industries	110	666	193	969	11.35	68.73	19.92	100.00
Clothing and leather manufacturing industries	52	531	114	697	7.46	76.18	16.36	100.00
Leather tanning industries	376	29	14	419	89.74	6.92	3.34	100.00
Wood manufacturing industries	58	211	61	330	17.58	63.94	18.48	100.00
Repair and maintenance of industrial devices	28	175	101	304	9.21	57.57	33.22	100.00
Non-metallic minerals manufacturing industries	27	213	52	292	9.25	72.95	17.81	100.00
Textile industries	7	181	30	218	3.21	83.03	13.76	100.00
Printing industries	24	115	42	181	13.26	63.54	23.20	100.00
Furniture manufacturing industries	13	84	13	110	11.82	76.36	11.82	100.00
Rubber and plastics industries	9	82	11	102	8.82	80.39	10.78	100.00
Electrical and electronic industries	12	53	23	88	13.64	60.23	26.14	100.00
Beverage industries	5	38	21	64	7.81	59.38	32.81	100.00
Paper-mill industries	7	43	13	63	11.11	68.25	20.63	100.00
Vehicle and means of transport manufacturing	6	29	19	54	11.11	53.70	35.19	100.00
Chemical industries	18	27	6	51	35.29	52.94	11.76	100.00
Metallurgy industries	8	24	12	44	18.18	54.55	27.27	100.00
Coke and petroleum products industries	2	16	1	19	10.53	84.21	5.26	100.00
Pharmaceutical industries	1	5	3	9	11.11	55.56	33.33	100.00
Tobacco industries	0	1	0	1	0.00	100.00	0.00	100.00
Other manufacturing industries	23	158	57	238	9.66	66.39	23.95	100.00
Total	871	3323	1043	5237				

indirectly using conversion factors (i.e., converting the number of inhabitants into population equivalents, p.e.), is equal to 1,800,000 p.e. for workers, increasing up to 2,550,000 p.e. including the inhabitants (Parliamentary Commission of Inquiry, 2006). In terms of density, there are 4404 p.e. km^{-2} in the Sarno River basin, which is 4 times more than the regional average (1063 p.e. km^{-2}). Considering the contribution of livestock activities, the p.e. can increase up to 14,450,000 p.e. km^{-2}.

According to Fig. 6, in 2004, the Sarno River presented from the confluence of its main tributaries 270 discharge points, including industrial (n = 70) and municipal (n = 142) wastewaters. The *Solofrana*, *Cavaiola* and *Alveo Comune Nocerino* were characterized by the presence of other discharge points, mainly of municipal wastewater: 135, 98 and 49, respectively (ARPAC, 2011).

5.2. Waste production

In the Sarno River basin, waste production is mainly associated with metal products and tannery industry manufacturing. Leather processing can produce an amount of waste that is greater than half of the raw processed material (UNIC, 2013), consisting of sludge from leather WWTPs and other by-products, such as fleshing, clipping and leather scrap. Between 2002 and 2005, the leather waste production decreased from 74,824 t to 20,915 t, similar to the national level (ISTAT, 1982-2010b).

When these wastes are not properly disposed in landfills, they can cause serious environmental concern due to the leaching of the contaminants into the soil. According to Agenzia Regionale per la Protezione dell'Ambiente Campania (ARPAC, 2009), the leather tanning industry managed very low quantities of fleshing and clipping compared to the theoretical balance of chrome tanning, probably due to the use of new technologies or the reuse of these products in other industrial sectors.

Currently, the annual amount of non-hazardous waste is still statistically estimated in more than half of the cases; thus, real knowledge is only partial and very far from the objective of all-waste tracking.

5.3. Air pollution

Air pollution contributes to the decreased environmental quality of the Sarno River catchment basin by the dry or wet deposition of

Table 3
Relation between inorganic contaminants and economic activities.

	Metals	Boron	Cyanides	Chlorides	Nitrates	Fluorides	Sulphates
Agriculture, livestock breeding, hunting and forestry	✓	✓			✓		✓
Mining	✓						
Production of food, beverages and tobacco	✓						
Production of textile materials and textile products	✓						
Production of leather and leather products	✓						
Manufacture of wood and wood products	✓		✓	✓	✓	✓	✓
Production of paper and paper products	✓		✓	✓	✓	✓	✓
Manufacture of coke, refined petroleum products and nuclear fuel	✓		✓			✓	✓
Production of chemical products and artificial fibres	✓	✓	✓	✓	✓	✓	✓
Production of rubber and plastic products	✓		✓	✓		✓	
Production of non-metallic mineral products	✓			✓		✓	
Production of metals and metal products	✓		✓			✓	
Production of machinery and equipment	✓						
Manufacture of electrical and optical equipment	✓						
Manufacture of transport equipment	✓			✓	✓	✓	✓
Supply of electricity, gas and water			✓		✓		✓

Table 4
Relation between organic contaminants and economic activities.

Economic activities	Aromatic	PAH	Chlorinated aliphatic		Nitrobenzenes	Chlorobenzenes	Phenols		Aromatic amines	Pesticides	PCB	PCDD, PCDF, PCB/DL
			Non-carcinogenic	Carcinogenic			Non chlorinated	Chlorinated				
Agriculture, livestock breeding, hunting and forestry	✓			✓	✓	✓	✓	✓	✓	✓	✓	
Production of leather and leather products	✓						✓					
Production of paper and paper products	✓		✓	✓		✓	✓	✓	✓		✓	✓
Manufacture of coke, refined petroleum products and nuclear fuel	✓	✓			✓		✓	✓				
Production of chemical products and artificial fibres	✓		✓	✓	✓	✓	✓	✓	✓		✓	
Production of rubber and plastic products	✓	✓	✓	✓		✓	✓	✓			✓	
Production of non-metallic mineral products												
Production of metals and metal products	✓		✓			✓		✓				✓
Manufacture of electrical and optical equipment	✓	✓	✓		✓	✓	✓	✓				
Manufacture of transport equipment	✓	✓	✓		✓	✓	✓	✓	✓			
Supply of electricity, gas and water		✓										

particles, but its quantification is currently not possible. According to ARPAC (2012), the Sarno River basin air quality needs to be improved in terms of SOx, NOx, volatile organic compounds (VOCs), NH_3 and particulate matter (PM10). The main sources of air pollution are the vehicular traffic and heating systems. The use of less-polluting cars by itself does not guarantee the sufficient reduction of emissions or comply with the new limits of European legislation (2008/692/EC; 2009/595/EC). However, between 1990 and 2005, emissions from industrial combustion and manufacturing processes decreased by 17% (Mancuso, 2010).

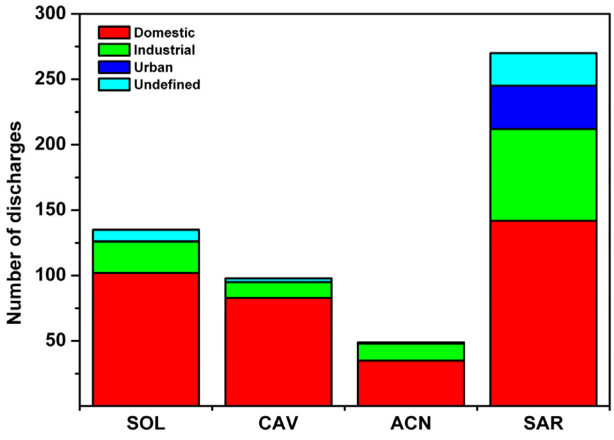

Fig. 6. Number of domestic, industrial, urban and undefined wastewaters discharged into the main water body of Sarno River and its tributaries. SOL = Solofrana stream, CAV = Cavaiola stream, CAN = Alveo Comune Nocerino and SAR = Sarno River (ARPAC, 2004).

A recent study from the Ministry of the Environment (MATTM, 2012) investigated the Sarno catchment basin's vulnerability to climate change at the municipal scale using an index integrating social, economic and environmental aspects. The index varying between 1 and 6 (i.e., I = 6 = low vulnerability) showed that more than half of the municipalities within the Sarno River catchment basin scored from medium (I = 4) to high (I = 2) vulnerability.

6. State and impacts

Water withdrawals in the Sarno catchment basin frequently supply drinking water (*Santa Maria la Foce* 0.5–1.0 $m^3\ s^{-1}$, *Mercato-Palazzo* 1.1 $m^3\ s^{-1}$ and *Santa Maria di Lavorate* 0.6–1.0 $m^3\ s^{-1}$) and irrigation (10,515 × $10^6\ m^3\ y^{-1}$ from Sarno plain wells). When excessive water withdrawals occur, the Sarno River water flow is primarily composed of domestic and industrial effluents, conferring its infamous reputation as the most polluted river in Europe. For example, ecotoxicological studies have evidenced micronuclei and DNA migration in *Gambusia holbrooki* collected from the river, suggesting the presence of strong genotoxic effects (Russo et al., 2004).

Over the years, the wastewater management has significantly improved, and the import of tanned leather has reduced the use and discharge of chemicals. However, the river environmental quality continues to be still very poor with potential adverse effects on the local population and ecosystem (Arienzo et al., 2001; Albanese et al., 2013a; Tornero and Ribera d'Alcalà, 2014). Public health is threatened by the consumption of contaminated water and food both directly and indirectly, such as in the case of watering horticultural products or feeding animals (Vigliotta et al., 2010; Maddaloni et al., 2014).

Irrigation with poor-quality water is one way that fruit and vegetables can become contaminated with food-borne pathogens, such as faecal coliforms. The accumulation of heavy metals in agricultural soils through wastewater irrigation leads to elevated heavy metal uptake by crops and thus affects food quality and safety. The consumption of food crops that are contaminated with heavy metals is a major food chain route for human exposure (Khan et al., 2008).

The extended biotic index as measured by ARPAC from 2002 to 2006 in 8 sampling sites indicated a highly critical status for the Sarno River ecosystem with the almost complete absence of benthic macroinvertebrates. Until 2009, the ecological status remained poor or bad (according to the classification that was established by the Italian Legislative Decree (LD) 367/03) with prevailing bad conditions once the observer moved from the spring to the river outlet. In 2011, the ecological status appeared bad along the entire course of the river. In contrast, its chemical status was good, with this apparent paradox being explained by specific changes in environmental quality standards (EQS) that were introduced by the Italian LD 260/2010. In some cases, the EQS were less stringent than those that were previously established by the Italian Ministry Decree (MD) 367/2003, such as in the case of the EQS for Cr that increased from 4 μg L^{-1} (MD 367/2003) to 7 μg L^{-1} (LD 260/2010). For example, according to LD 260/2010, Cr concentration contributes to the definition of a river ecological status but not of a chemical one. Consequently, despite the bad ecological status of the Sarno River and the presence of an excess amount of Cr compared to the EQS along the entire watercourse (e.g., 31 μg L^{-1} as the maximum value), the chemical status was good (ARPAC, 2014).

Between 2003 and 2009, macrobenthic descriptors indicated poor or bad environmental quality for *Solofrana* and *Alveo Comune Nocerino* that drained contaminants from all of the Sarno flatland. In 2010 and 2011, according to ARPAC (2009, 2014), the ecological status of *Solofrana* and *Alveo Comune Nocerino* remained bad.

Data from ARPAC (2012, 2014) and Legambiente (2014) (Fig. 7) showed that the chemical oxygen demand (COD) and $N–NH_4^+$ concentrations increased significantly in *Alveo Comune Nocerino* compared to those in Upper Sarno, whereas this trend was less evident for $N–NO_3^-$ and total phosphorous.

No apparent trend in the COD, $N–NH_4^+$, $N–NO_3^-$ or total phosphorous concentration was noticed between 2003 and 2014. The average levels of $N–NH_4^+$, $N–NO_3^-$ and total phosphorous concentrations exceeded the threshold levels of 0.24, 4.8 and 0.4 mg L^{-1} as established by the LD 260/2010, respectively. No threshold was available for COD. The slight decrease in $N–NO_3^-$ and total phosphorous concentrations over the years may be associated with the reduction of agricultural activities as shown in Fig. 5. According to Fig. 6, several treated and untreated discharges continued to strongly affect the quality of the river, having wastewater of domestic, industrial, urban or still unknown origin. In 2014, *Solofrana* and *Cavaiola* contributed to the inorganic pollution of the Sarno River as summarized in Fig. 8. Water samples that were

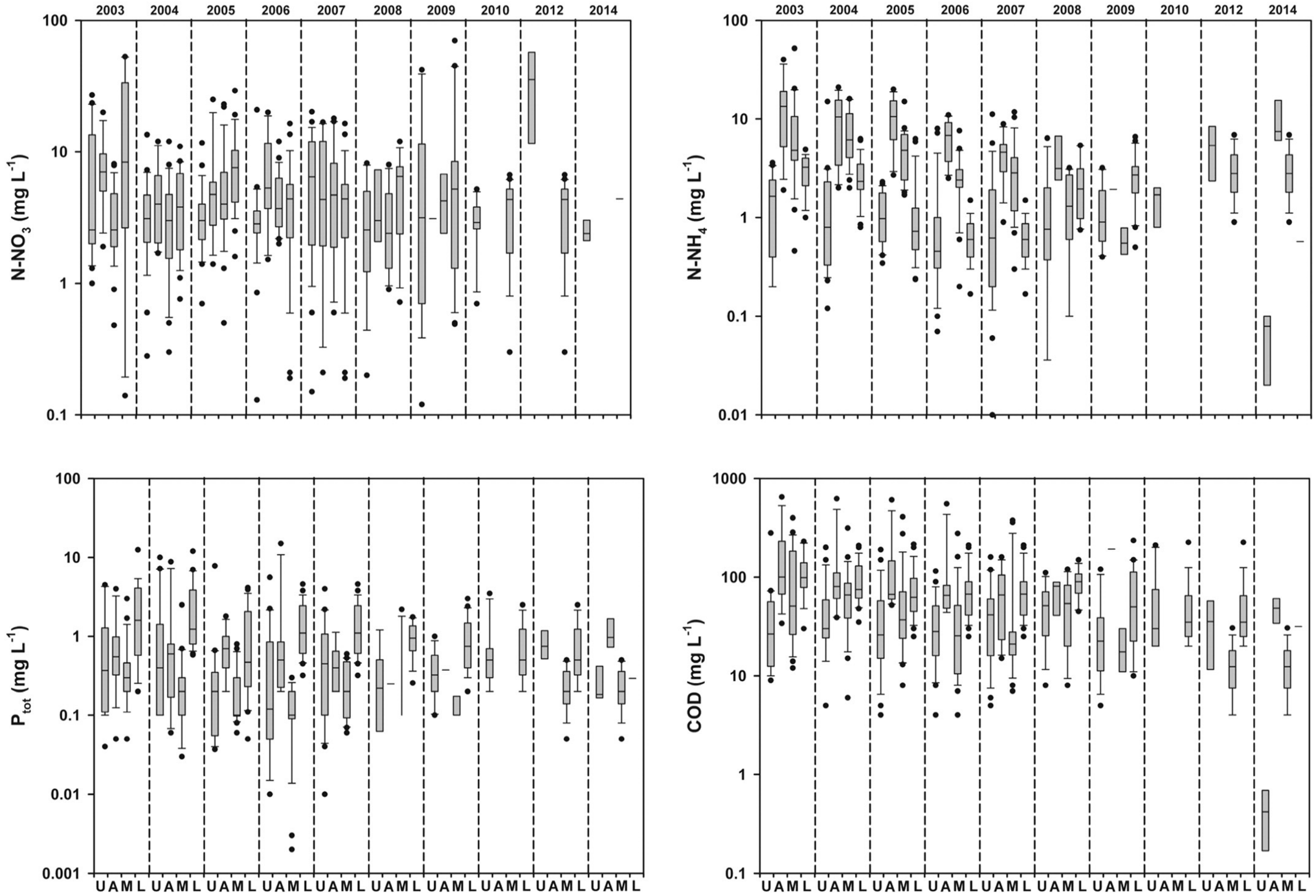

Fig. 7. Box plot for $N–NO_3^-$, $N–NH_4^+$, P_{tot} and COD in the Upper Sarno (U), *Alveo Comune Nocerino* (A), Middle Sarno (M) and Lower Sarno (L) districts within the period 2003–2014 (ARPAC, 2003–2012; Legambiente, 2014).

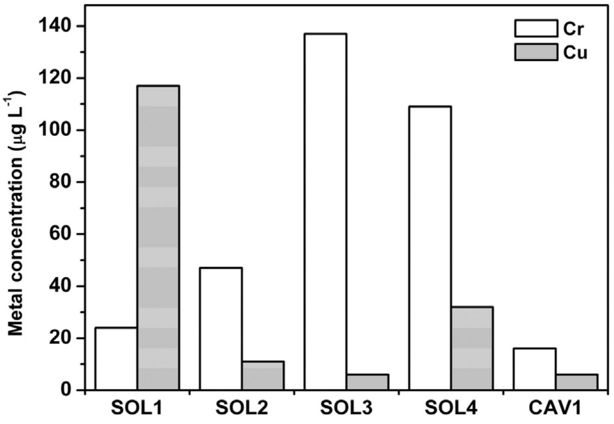

Fig. 8. Water concentration of Cr and Cu in four stations of the *Solofrana* stream (SOL1, 40° 49′ 06.53″ N, 14° 47′ 13.33″ E; SOL2, 40° 47′ 38.35″ N, 14° 45′ 39.46″ E; SOL3, 40° 46′ 01.18″ N, 14° 39′ 23.28″ E; SOL4, 40° 44′ 41.43″ N, 14° 38′ 44.90″ E) and in one station of the *Cavaiola* stream (CAV1, 40° 44′ 26.24″ N, 14° 39′ 46.55″ E) in 2014 (Legambiente, 2014); sampling stations were displayed in Fig. 1.

collected from *Solofrana* indicated the presence of Cr and Cu at up to 137 and 117 μg L^{-1}, respectively (Legambiente, 2014), while the loads of Cr and Cu from *Cavaiola* were lower.

Arienzo et al. (2001) reported a reduction of heavy metals between 1975 and 1998. According to Fig. 9, this trend was confirmed between 1998 and 2014 for Cu and Pb, whereas no significant changes could be observed for Cr or Zn (; Legambiente, 2014, ARPAC, 2003–2012). The trend of Pb could be influenced by the progressive introduction of unleaded fuels in Italy (98/70/CE). The presence of Cu may be explained by its agricultural use throughout the basin, and its slight decrease could be associated, as for nitrates and phosphorous, with reduced food- and feed-production activities. As for other contaminants, the concentration of some metals increased in *Alveo Comune Nocerino* at the point where *Solofrana* and *Cavaiola* converge.

During the 2002 fall season, Albanese et al. (2013a, 2013b) assessed 89 sediment samples that were collected all along the Sarno River looking for metalloid and metal contamination. The results indicated that the mountainous and hilly areas of the catchment were poorly impacted compared to the moderately or highly contaminated samples that were collected from the flatland, including *Solofrana stream*. High concentrations of Cr (810 mg kg^{-1} — maximum Cr concentration between *Bracigliano* and *Mercato San Severino*) and Cu (1556 mg kg^{-1} — maximum Cu concentration) were found in the soil samples (Cicchella et al., 2014), suggesting that the Sarno River can adversely affect neighbouring lands, especially during flooding events. The small size of the Sarno River basin and the steep slopes of the catchments of its tributaries lead to short inflow response time as bankfull discharges due to exceptionally intense rainfall even after a few hours. The intense human impact along the riverbanks does not allow for the natural lamination of bankfull discharges. Sections of the lower stretch of the river do not support the flow. The surrounding areas are frequently flooded, resulting in significant damage to horticultural crops. The extensive use of river water for irrigation and the frequent flooding events have produced a widespread contamination of soils by metalloids and heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) (Adamo et al., 2003). Cicchella et al. (2014) investigated the presence of Cr, Cu, Hg, Pb, Sb,

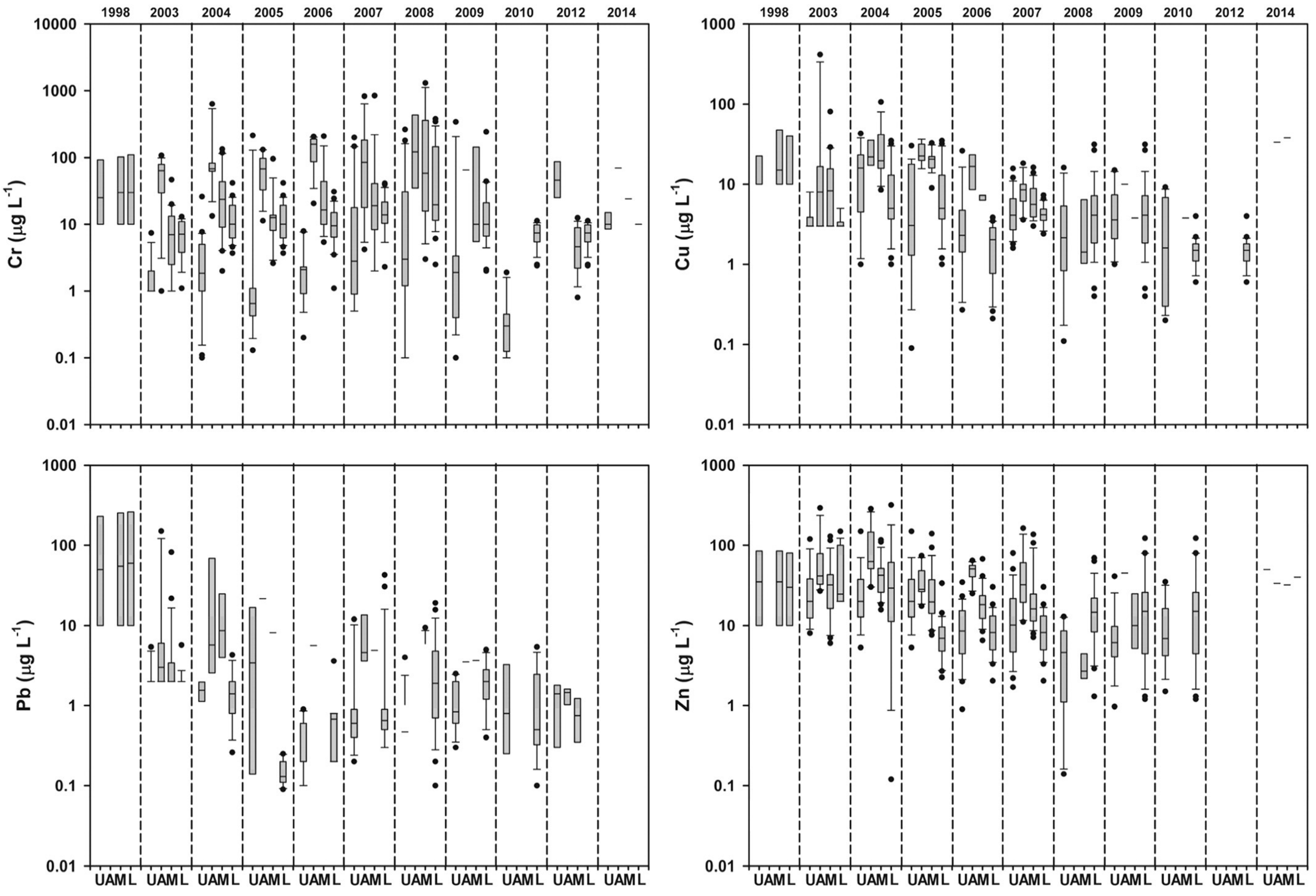

Fig. 9. Box plot for Cr, Cu, Pb and Zn in the Upper Sarno (U), *Alveo Comune Nocerino* (A), Middle Sarno (M) and Lower Sarno (L) districts within the period 2003–2014 (ARPAC, 2003–2012; Legambiente, 2014).

Table 5
Comparative sediment concentrations of Cu, Cr, Pb and Zn in populated river basins worldwide.

Cu (mg kg^{-1})	Cr (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	River	References
17–956	5–1118	19–229	39–512	Sarno (Italy)	Albanese et al. (2013a)
12–78	34–108	16–128	90–691	Elbe River (Germany)	Wetzel et al. (2013)
18–25	–	24–37	124–1300	Missisipi River (USA)	Santschi et al. (2001)
18–47	–	5–269	1–144	Lower Brisbane River (Australia)	Olmos and Birch (2008)
15–197	36–2714	18–93	66–1535	Gaoping River (Taiwan)	Doong et al. (2008)

Sn and Zn in 283 topsoil (0–20 cm) samples throughout the Sarno River basin. As expected, hot spots of Cr appeared in the *Solofrana* valley (i.e., tannery industries), while Cu contamination was associated with agricultural practices. Anomalies in the Cd, Hg, Pb, Sb, Sn and Zn concentrations were mainly found in urban and industrial areas (i.e., high-traffic roads) due to the high pressures that are produced by population growth.

Currently, the amount of metalloids and metals that are detected in the water-dissolved phase, suspended particulate matter and sediment makes the Sarno River one of the main sources of contamination for the entire Gulf of Naples (Montuori and Triassi, 2012). The estuary of this river is affected by moderate As and Hg contamination but high concentrations of Cd, Cr, Cu, Pb and Zn as well as other trace metals (Manfra and Accornero, 2005). According to Table 5, the concentrations of Cu, Cr, Pb and Zn in the Sarno River sediments were on average greater than those of other populated river basins worldwide. Polychlorinated biphenyls (PCBs) presented concentrations that were higher than the recommended thresholds (Tornero and Ribera d'Alcalà, 2014), such as for 1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethylene (DDE) and 1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethane (DDD) (11.2 μg kg^{-1}), the presence of which indicated the illegal use of 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane (DDT) (Scarpato et al., 2010). In 2011, the average concentration in the water of the organophosphate insecticide dimethoate was 0.8 μg L^{-1}, which is 0.3 μg L^{-1} above the relative EQS (ARPAC, 2012).

The polycyclic aromatic hydrocarbons (PAHs) in the Sarno River (i.e., water, suspended particulate matter and sediment) and their impact on the Gulf of Naples were assessed for the first time in 2012 (Montuori and Triassi, 2012). According to Table 6, the concentrations of PAHs in the Sarno River were on average greater than or similar to those of other populated river basins worldwide.

Sarno River PAHs presented prevailing pyrolytic patterns, reflecting the discharge of industrial wastes along with combustion-derived PAHs, in addition to perylene, which is of mainly natural diagenetic origin. The emissions from factories and Naples sub-urban areas increased the contribution of PAHs in the Sarno River also due to fall-out events. Other inputs originated from road dust, road runoff and untreated municipal wastewater (Vigliotta et al., 2010). Thus, the Sarno River flowing through the flatland drains various inputs of PAHs, reaching concentrations of up to 489 ng L^{-1} (Montuori and Triassi, 2012).

Table 6
Comparative concentrations of PAHs in populated river basins worldwide.

PAHs concentration (ng L^{-1})	River	References
12.4–1105.9	Sarno (Italy)	Montuori and Triassi (2012)
52–280	Elbe River (Germany)	Götz et al. (1998)
25–433	Missisipi River (USA)	Mitra and Bianchi (2003)
5.1–12	Lower Brisbane River (Australia)	Shaw et al. (2004)
10.0–9400	Gaoping River (Taiwan)	Doong and Lin (2004)
179–369	Middleand Lower Yellow River (China)	Li et al. (2006)
21.7–138	Xijiang River (China)	Deng et al. (2006)
70.3–1844.4	Qiantang River (China)	Chen et al. (2007)

The compliance of the surface water quality with the European Commission (EC) EQS is verified considering the annual average values resulting from the sum of dissolved and suspended particulate matter concentrations obtained on a monthly basis (Common Implementation Strategy for the Water Framework Directive, 2005; EC, 2009). In the Sarno River water, Montuori and Triassi (2012) showed that the benzo(a)pyrene (BaP) average concentration (63.9 ng L^{-1}) was higher than the relative EQS value (50 ng L^{-1}); the sums of benzo(k)fluoranthene and benzo(a)fluoranthene (BkF + BbF) (98.1 ng L^{-1}), and benzo(ghi)perylene and indeno[1,2,3-cd]pyrene (BghiP + InD) (126.8 ng L^{-1}) were significantly higher than the EQS (30 and 2 ng L^{-1}, respectively), indicating potential hazards for the river health status.

Maddaloni et al. (2014) investigated the presence of illicit drugs (i.e., cocaine, heroin, codeine, morphine and 9-Ene-Tetrahydrocannabinol) and their metabolites in water samples, evidencing further environmental hazards. Cocaine (13 ± 2 ng L^{-1}) and benzoylecgonine (91 ± 10 ng L^{-1}), a cocaine metabolite, showed concentrations that were similar to the average Campania Region levels but higher than those detected in the Po River (1.2 ± 0.2 ng L^{-1}) (Italy), Arno River (1.7 ± 1.2 ng L^{-1}) (Italy), and Thames River (UK) (4.0 ± 0.1 ng L^{-1}) (Zuccato et al., 2005; Maddaloni et al., 2014).

7. Responses

7.1. Water and wastewater management

Since the 1970s, the rehabilitation and redevelopment of Sarno River basin have been important issues for the economic development of the Campania Region, granting a better quality of life. The Campania Region is an internationally renowned touristic area not only for its historical attractions but also for swimming and leisure activities along the coastline, especially during summertime. Tourism helps develop local infrastructures and services and represents the major source of income and employment, as well as a source of pollution, especially through the wastewater that is discharged into the sea. Consequently, the analysis, maintenance and improvement of marine environmental quality in the region are major issues not only for the welfare of the entire ecosystem but also for social and economic reasons (Tornero and Ribera d'Alcalà, 2014).

The absence of sewage systems, the lack of WWTPs and supply pipelines, the poor state of the surface water quality, and the widespread practice of dumping any type of waste into the riverbed have transformed the Sarno River into one of the most polluted rivers in Europe. In April 1995, a socio-economic and environmental emergency state was declared by the national government, and a commissioner was established with extraordinary powers and specific financial resources to provide before December 1995 the necessary measures to overcome the crisis. However, despite several extensions up to March 2003, the goals were not met. Since 1997, a remarkable lag was experienced in implementing the planned initiatives mainly due to the lack of the required involvement of the Campania Region and the institution of Sarno River Basin Authority and the overlap, fragmentation and duplication of actions that were not coordinated. Sanitary criticisms grew due to the reduced effectiveness of controls and institutional inertia. From March 2003 to June 2011, the new commissioner (Order of the President of the Council of Ministry, OPCM, 3270/2003) carried out the construction of four WWTPs (*Nocera*, *Angri*, *Sant'Antonio Abate/Scafati*, and *Castellamare*), the implementation of 50 km of collectors and several interventions to complete the sewerage systems for approximately 700 km mainly within urban areas, the hydraulic dredging of various stretches of the river and the construction of interim storage sites and treatment of dredged sediments. These compulsory and urgent works presented severe slowdowns due to their complexity.

Today, the wastewater treatment system of Upper Sarno is composed of two WWTPs serving 300,000 p.e., which is approximately 12% of the total need. The WWTP of *Mercato San Severino*, which was designed for the treatment of municipal and industrial wastewater, has been operational since 1995. The WWTP in *Solofra* was designed as a pre-treatment of tanning wastewater before its discharge into *Mercato San Severino* WWTP. In operation since 1995, this WWTP was initially constituted by a physical–chemical treatment that was subsequently upgraded with a biological stage.

The Middle Sarno treatment capacity is approximately 1,725,000 p.e. split into three WWTPs, *Nocera*, *Angri and Sant'Antonio Abate/Scafati*, which became operative only in 2006, 2007 and 2009, respectively, meaning that only 58% of the total p.e. is effectively treated. The *Nocera* WWTP, based on activated sludge processes, was designed to treat up to 300,000 p.e. Although the primary sedimentation is missing, the WWTP is equipped with an anaerobic digester for sludge treatment. The *Angri* WWTP was designed to treat approximately 308,000 p.e. The wastewater passes through a coarse screen before microscreening, de-sanding, de-oiling and pre-aeration units. After the primary treatment, wastewater is conveyed to de-phosphatizing, denitrification, oxidation, and nitrification units. Three anaerobic digesters and continuous dynamic thickeners characterize the sludge line. The *Sant'Antonio Abate/Scafati* WWTP was designed to treat 400,000 p.e. with a conventional activated sludge process. Neither the *Nocera* nor *Angri* WWTP works at full regime because some stretches of the sewer systems are not yet completed. In the case of the *Sant'Antonio Abate/Scafati* WWTP, the main collector that is already completed is not operational due to bureaucratic constraints. The Lower Sarno WWTP located in *Castellammare di Stabia* was designed for 500,000 p.e., which is only the 21% of the total need. Currently, the WWTP treats only 200,000 p.e. The biological wastewater treatment line, which was designed in 2004 and completed in 2010, became operational only in April 2014, meaning that after the cholera epidemic, untreated wastewater was discharged for 40 years in the Gulf of Naples.

7.2. Waste management

Waste management represents a key stressing element for water quality. The EC referred Italy to the European Court of Justice because of the inadequacy of the Campania Region plants for waste treatment and disposal. Thus, in 2012, the Campania Region adopted the Regional Plan for Urban and Special Waste Management that is currently ongoing.

The Sarno River basin was included amongst the contaminated sites of national interest (Law 266/2005). The site interim perimeter (Ministerial Decree 11th August 2006) comprised all of the municipalities falling within the catchment basin ($n = 38$), in part or as a whole. The 2013 Regional Plan for the Remediation of Contaminated Sites (Campania Regional Council, 2013) changed the borders of the area as a consequence of the results of specific campaigns for pollution monitoring. On 11 January 2013, the Minister of the Environment, Land and Sea signed a decree downgrading 18 heavily polluted sites from national to regional concern, including the catchment area of Sarno River. Surprisingly, the guidelines, containing methods and parameters for the preliminary investigation of contaminated samples from the Sarno River (Art. 242 Italian LD 152/2006), were published only in April 2014 (Campania Regional Council, 2014).

7.3. Air pollution prevention

In recent years, several EC directives have stimulated the regulation of air quality at the national level originating i) the LD 155/2010 (2008/50/EC; 2004/107/EC) providing the threshold limit values for air quality and forcing Regions and Autonomous Provinces to arrange plans for air quality improvement in the case of "non-compliance"; and ii) the LD 171/2004 setting the limits for some specific air pollutants (i.e., SO_2, NO_x, volatile organic compounds and ammonia) (Gothenburg Protocol — Convention on Long-Range Transboundary Air Pollution and 2001/81/EC — National Emission Ceiling). Further legislative requirements about air quality were implemented in specific sectors, such as in the case of emissions from vehicles (EC Regulations 692/2008/EC; 595/2009/EC) or industrial exhaust (Directive, 2010/75/EC). The air quality plan of Campania Region was elaborated in 2005 (Regional Decree 167/2006) and needs to be urgently updated.

8. Conclusions and outlook

The current review highlighted that the environmental status of Sarno River and part of its catchment basin represent a really great concern due to their long-lasting exploitation. Wastewater generated by agriculture and agri-food industries in the flatland of Sarno River and tanneries in Solofrana valley have heavily affected the quality of water, sediment and soil. Their monitoring is also difficult because no EU regulation about food products environmental impact still exists. Countermeasures must be taken as soon as possible to start remediating this risky situation. A list summarising the major issues and actions that could be tackled follows:

- Adoption of measures to reduce the pollution load from industrial waste, handicraft, agricultural activities, even with restrictions on the use of raw materials and replacement of products including technology updates and specific separation of wastes to be treated in dedicated facilities;
- Adoption of measures to increase and improve the treatment capacity of urban and industrial WWTPs in order to promote wastewater reuse;
- Adoption of measures to improve the volume of water flowing in the Sarno River basin reaching the so-called minimum vital flow for example reducing agricultural water withdrawals thanks to innovative irrigation systems;
- Construction of new sections within the existing sewers and new wastewater collectors supporting effluent reuse or discharge in conditions of maximum security;
- Stringent control of discharge points not complying with the threshold limit values by competent authorities focusing on metals (e.g. Cr and Cu) and PAHs;
- Strengthen the support of wastewater and waste reduction, recycle and reuse within the perspective of secondary raw materials production as well as the closure of cycles (i.e. water cycle);
- Overcoming the bureaucracy slowing down the approval of executive projects of utmost urgency for the area;
- Lowering the traditional agricultural practices highly dependent on agro-chemicals supporting biologically (integrated) agriculture;
- Development of river contracts as social tools involving local land and water users promoting river management and environmental protection.

Certainly, the restoration of the minimal vital flow and the definition of Sarno River contract can be the most viable, cost-effective and immediate solutions to be considered by policymakers to start redeveloping this sick river. Focused investments are necessary to support all other actions on a medium- and long-term basis like as a strong involvement of policymakers, lawmakers and stakeholders at all levels (municipal, regional, national and European).

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