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A holistic picture of spatial distribution of river polluting loads in a highly anthropized area

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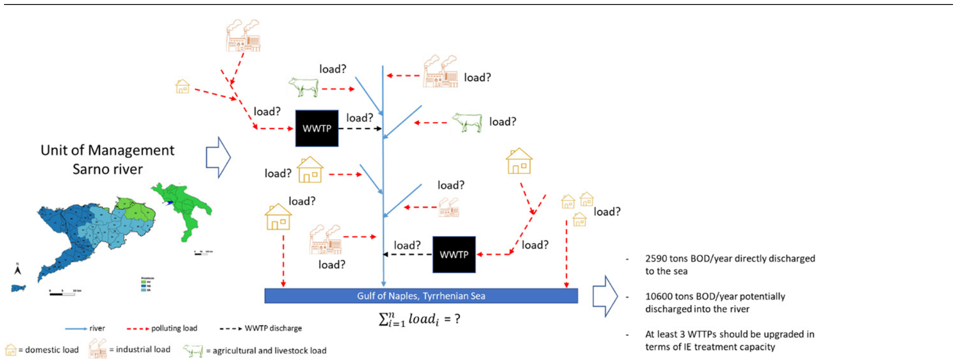
HIGHLIGHTS

- Sarno flatland bears highest organic and nitrogen polluting loads.
- Nitrogen load is mainly influenced by industrial activities.
- Highest phosphorous loads are localized along the coast and in Sarno flatland.
- Wastewater management along the cost and in the Middle Sarno is still inadequate.

GRAPHICAL ABSTRACT



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ABSTRACT

For many years, there has been a debate on the polluting loads affecting the Gulf of Naples, one of Italy's most spectacular and iconic landscape. The wide territory bordering the Gulf includes the Sarno river basin (SRB) managed by the Southern Apennines River Basin District Authority in the framework of Unit of Management Sarno (UoM-Sarno). The paper investigated the anthropogenic pressures and their spatial distribution in the UoM-Sarno, revealing as SRB represents a *hotspot* of pollution mainly due to the high population density and widespread hydro-demanding activities which are responsible of high organic and eutrophication loads. The pollution sources, variably distributed on the area, and potentially conveyed to the wastewater treatment plants (WWTPs) located into SRB, were estimated considering the WWTPs treatment capacity as well. Results revealed a holistic picture of UoM-Sarno area allowing to establish the priorities of the interventions aimed at safeguarding the coastal marine resources. In particular, 2590 tons BOD/year were directly discharged into the Gulf of Naples due to the missing of sewers, and other 10,600 tons BOD/year are potentially discharged in the Sarno river reaching the sea, considering the contribution of population, industrial activity, and livestock.

1. Introduction

To establishing a framework for Community action in the field of water policy, the Water Framework Directive (WFD, 2000/60/EC) instituted River Basin District Authority (RBDA) to coordinate and manage the area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters. As consequence of

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the application of WFD, 110 RBDA were identified in Europe and seven of them are located in Italy. The Southern Apennines River Basin District Authority is the second largest one of Italy, managing an area wider than 68.000 km^2, including the Unit of Management Sarno (UoM-Sarno), located in Campania Region. The UoM-Sarno is characterized by the presence of natural landscape and historical architectural beauties of recognized value such as archeological remains of Pompei and Ercolano (Vignola et al., 2022), and valuable crops associated with supply chains of significant importance (Pindozzi et al., 2016), not only for the direct economic weight on the internal economy and for the contribution to the Southern economic system, but also for the high induced effects they can generate at national and international levels. The Sarno river basin (SRB), one of the most polluted river basins in Europe, falls within the territorial framework of the UoM-Sarno. The SRB is characterized by a jumble of complex management criticalities from a socio-economic-environmental and health point of view (Arienzo et al., 2001; Lofrano et al., 2015; Cicchella et al., 2016; Mobilia et al., 2023; Vitale et al., 2023). The heterogeneous territorial context is characterized by a mixture of uses and functions that is found in the contextual presence of industrial, domestic, and agricultural activities, whose promiscuity produces a widespread territorial disorder. As consequence, SRB is a hotspot area for water contamination suffering from the presence of more than one million inhabitants and a still inadequate wastewater management (Basile et al., 2015; Lofrano et al., 2015; Papa et al., 2017; Baldantoni et al., 2018).

The Sarno river plain 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 favorable climatic conditions (Albanese et al., 2013; Qu et al., 2016; Thiombane et al., 2018). The upper part of the UoM-Sarno hosts the third Italian leather tannery district, being tannery favored by pastoralism and freshwater availability since prehistoric times.

A large part of the population lives along the coasts using marine resources for related activities to produce income or for recreational purposes, contributing to increase anthropogenic pressure on coastal area up to exceeding the receptive capacity of the marine environment (Pagnotta and Barbiero, 2003). The main effects on the marine environment linked to the release of contaminants from the mainland through Sarno river can be shortlisted as follows: i) alteration of the hygienic characteristics (microbiological contamination); ii) variation of the trophic level (nutrients); iii) hypoxia and anoxia (nutrients and hydrocarbons); iv) toxicity and bioaccumulation (organic micropollutants and inorganics). While human activities have significantly impacted the riverine ecosystem and the water quality of the Gulf of Naples, the loads of pollutants have never been estimated.

The pollution loads assessment is necessary to properly manage highly anthropized area, to define priorities in the allocation of funds for wastewater treatment plants potential upgrade and the construction of sewers. Previous studies highlighted the importance of depicting the amount and the spatial characteristic of pollution loads from different sources in the river basins (Zhang et al., 2020; Wang et al., 2020; Xiao et al., 2023). However most studies focused on specific pollution sources (Liu et al., 2020; Wang et al., 2020) or pollutants (Zhang et al., 2020) or were based exclusively on experimental data (Gao et al., 2022). The influence of economic development of the investigated areas has hardly ever been taken into consideration.

To achieve a holistic picture of spatial distribution of river polluting loads, this study identified and investigated the existing pressures onto the UoM-Sarno, and estimated the organic (BOD_5) and eutrophication (nitrogen and phosphorous) loads based on the contribution of different sources (domestic, industrial, zootechnical, and agricultural) between 2011 and 2018.

The aim of the study was to provide a holistic picture of the environmental pressures affecting the water quality supporting the identification of sustainable remedial actions. Such evaluation is a compulsory prerequisite to estimate the areas at greatest environmental risk and define the correct control monitoring plans, establishing the priorities of the actions aimed at safeguarding the riverine environment and the coastal marine resources. The article intends to provide an operational tool for the implementation of the WFD at the European level with particular reference to the activities of the River Basin District Authority (RBDA) in the coordination and management of vast areas.

2. Area of study

The UoM-Sarno extends for about 700 km^2 between Mar Tirreno at West and the Picentini mountain range at East, Somma-Vesuvio complex at North and Sorrento Peninsula with Capri Island at South.

It includes 74 municipalities belonging to three different provinces, Salerno (26 municipalities), Avellino (9 municipalities), and Naples (39 municipalities) as shown and listed in Fig. 1.

The SRB is a portion of UoM with a surface area of about 428.67 km^2 consisting of three sub-basins, Solofrana, Cavaiola and the Sarno catchments.

3. Land uses

According to Fig. 2, among the 74 municipalities belonging to the UoM-Sarno, only 52 municipalities showed an urbanized area, 61 presented a cultivated agricultural area and 60 an uncultivated agricultural area.

The extension for the three different UoM-Sarno land uses are reported in Table 1. The agricultural area takes up most of the study area with the 44.2 % of the total, while the uncultivated area and the artificial area are the 35.9 % and the 19.8 %, respectively.

4. Methodology

The polluting loads generated in the UoM-Sarno were estimated following the procedures identified by the Italian Water Research Institute (Pagnotta and Barbiero, 2003) by using appropriate conversion coefficients reported in literature studies and specifically estimated respect to some economic activities such tannery industries. For the theoretical estimations of the polluting loads, data from ISTAT census surveys from 2011 to 2018 were used.

The organic pollution load (OPL) was calculated as the sum of four different BOD_5 contributions (Eq. (1)) produced by resident population (BOD_5^{RP}), floating population (BOD_5^{FP}) (i.e., tourists), hydro-demanding economic activities (BOD_5^{I}) and zootechnical activities (BOD_5^{Z}).

$$\mathrm{OPL} = BOD_5^{RP} + BOD_5^{FP} + BOD_5^{I} + BOD_5^{Z} \tag{1}$$

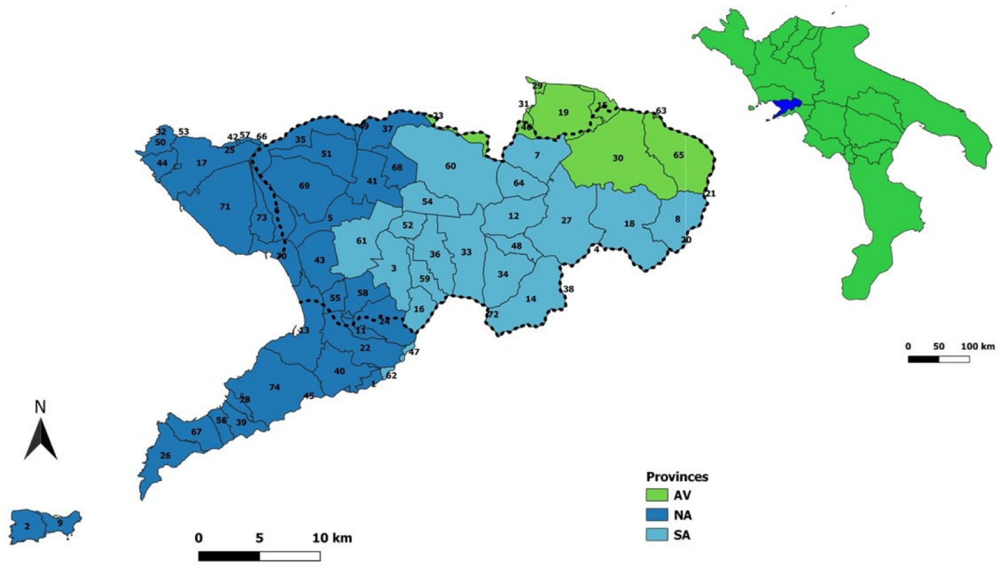
The total phosphorus (EL_P) and nitrogen (EL_N) loads were derived by the sum of two different groups of loads: i) diffused sources (cultivated ($DS_{N,P}^{C}$) and uncultivated ($DS_{N,P}^{U}$) soil, and zootechnical activities, $DS_{N,P}^{Z}$) and ii) localized sources (legal resident population ($LS_{N,P}^{RP}$), floating population ($LS_{N,P}^{FP}$) and hydro-demanding economic activities ($LS_{N,P}^{I}$)) according to the Eqs. (2) and (3):

$$EL_N = DS_N^C + DS_N^U + DS_N^Z + LS_N^{RP} + LS_N^{FP} + LS_N^I \tag{2}$$

$$EL_N = DS_N^C + DS_N^U + DS_N^Z + LS_N^{RP} + LS_N^{FP} + LS_N^I \tag{3}$$

4.1. Population

The resident population (RP) data per each municipality in the UoM-Sarno were derived from the General Population Census of Italy (ISTAT 2011 and 2018).



Nr.	Municipality	Nr.	Municipality	Nr.	Municipality
1	Agerola	26	Massa Lubrense	51	San Giuseppe Vesuviano
2	Anacapri	27	Mercato Sanseverino	52	San Marzano sul Sarno
3	Angri	28	Meta di Sorrento	53	San Sebastiano al Vesuvio
4	Baronissi	29	Monteforte Irpino	54	San Valentino Torio
5	Boscoreale	30	Montoro	55	Santa Maria la Carità
6	Boscotrecase	31	Moschiano	56	Sant'Agnello
7	Bracigliano	32	Napoli	57	Sant'Anastasia
8	Calvanico	33	Nocera Inferiore	58	Sant'Antonio Abate
9	Capri	34	Nocera Superiore	59	Sant'Egidio del Monte Albino
10	Carbonara di Nola	35	Ottaviano	60	Sarno
11	Casola di Napoli	36	Pagani	61	Scafati
12	Castel San Giorgio	37	Palma Campania	62	Scala
13	Castellammare di Stabia	38	Pellezzano	63	Serino
14	Cava de' Tirreni	39	Piano di Sorrento	64	Siano
15	Contrada	40	Pimonte	65	Solofra
16	Corbara	41	Poggiomarino	66	Somma Vesuviana
17	Ercolano	42	Pollena Trocchia	67	Sorrento
18	Fisciano	43	Pompei	68	Striano
19	Forino	44	Portici	69	Terzigno
20	Giffoni Sei Casali	45	Positano	70	Torre Annunziata
21	Giffoni Valle Piana	46	Quindici	71	Torre del Greco
22	Gragnano	47	Ravello	72	Tramonti
23	Lauro	48	Roccapiemonte	73	Trecase
24	Lettere	49	San Gennaro Vesuviano	74	Vico Equense
25	Massa di Somma	50	San Giorgio a Cremano		

Fig. 1. Area of municipalities inclued in UoM Sarno. The dotted line marks the boundaries of the SRB. AV: Avellino Province; NA: Naples Province; SA: Salerno Province. In the gray cells, 38 municipalities belonging to SRB.

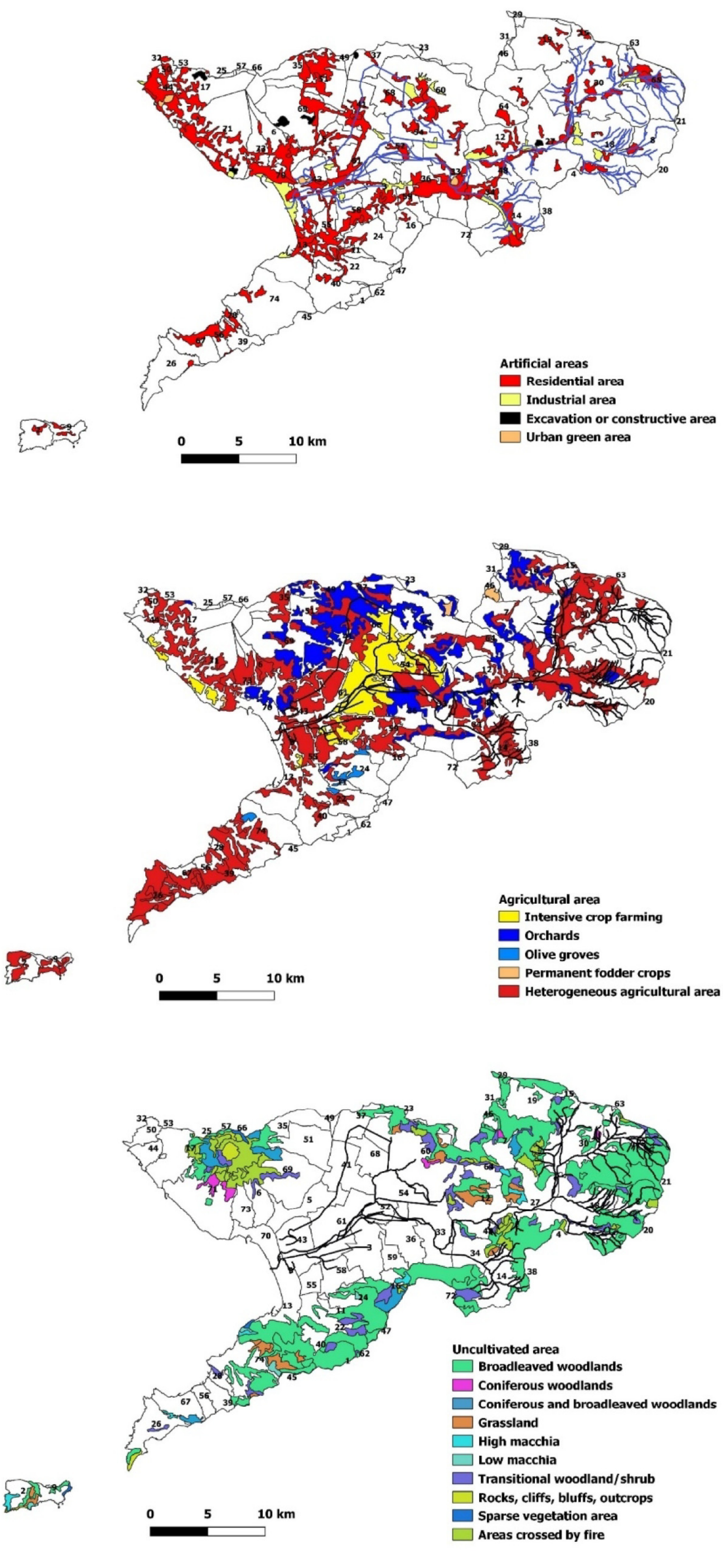


Fig. 2. Spatial distribution of a) aritificial area; b) agricultural area; c) uncoltivated area per each municipality belonging to UoM-Sarno.

Table 1
Extension of the different areas of UoM-Sarno.

Area	Extension (km^2)
Artificial area	140.27
Agricultural area	313.30
Uncultivated area	254.56

The OPL contribution produced by RP in one year per each municipality was obtained according to Eq. (4):

$$BOD_5^{RP}\left(\frac{ton}{year}\right) = \frac{IE^{RP} \cdot 60 \cdot 365}{1000000} \tag{4}$$

where the inhabitants equivalent (IE^{RP}) are equal to the legal resident inhabitants in the municipality.

The nitrogen and phosphorus loads produced in one year by RP ($LS_{N,P}^{RP}$) (Eq. (5)) have been assessed using the coefficients $Cf_{N,P}$ reported in Table 2.

$$LS_{N,P}^{RP}\left(\frac{ton}{year}\right) = \frac{Cf_{N,P}^{RP} \cdot IE^{RP} \cdot 365}{1000000} \tag{5}$$

4.2. Floating population

The floating population (*FP*) data per each municipality in the UoM-Sarno were obtained by ISTAT (2011 and 2018). The OPL contribution produced by *FP* in one year per each municipality was obtained according to Eq. 6:

$$BOD_5^{FP}\left(\frac{ton}{year}\right) = \frac{IE^{FP} \cdot 60 \cdot 365}{1000000} \tag{6}$$

where IE^{FP} is the average number of visitors hosted in hotels or other accommodation facilities in each municipality in one year and is equated to one resident inhabitant.

The nitrogen and phosphorus loads produced in one year by *FP* ($LS_{N,P}^{FP}$) (Eq. (7)) have been assessed using the coefficients $Cf_{N,P}$ reported in Table 2.

$$LS_{N,P}^{FP}\left(\frac{ton}{year}\right) = \frac{Cf_{N,P}^{FP} \cdot IE^{FP} \cdot 365}{1000000} \tag{7}$$

4.3. Economic activities

For the evaluation of the OPL value of hydro-demanding economic activities in one year per each municipality, a conversion criterion was used to obtain the IE^I based on the following knowledge: i) the types of production that carry out activities involving a potential discharge of polluted waters; ii) the number of workers to each typology (W_i); iii) the availability of transformation coefficients (Cf_i) according to the type of activities. The types of activity and the number of workers were extrapolated by the Industry and Services census (ISTAT 2011–2018). About the transformation coefficients, the values proposed by Barbiero et al. (1998) and reported in Table 3, were adopted. The total IE^I for all industrial components of the polluting load per each municipality was obtained by Eq. (8):

$$IE^I = \Sigma_i W_i \cdot Cf_i \tag{8}$$

Table 2
Eutrophication coefficients (Pagnotta and Barbiero, 2003).

Determinants	Cf_N	Cf_P	Unit
Resident Population (RP)	6.16	0.92	g/IE/d
Floating Population (FP)	6.16	0.92	g/IE/d
Industrial activities (I)	27.40	10 % LS_P^{PR}	g/W/d
Cultivated soil (C)	43.83	1.64	g/ha/d
Uncultivated soil (U)	5.48	0.27	g/ha/d

Table 3
Transformation coefficients (*Cf*) for hydro-demanding economic activities (Barbiero et al., 1998; Masotti, 2002).

Industrial activities	*Cf*	Industrial activities	*Cf*
Mining of coal and lignite; peat extraction	20	Non-metallic minerals manufacturing industries	1.5
Extraction of crude oil e of natural gas; related services	30	Metal manufacturing industries	2.3
Mining of uranium and thorium ores	0.6	Manufacturing of metal products, excluding devices	2
Mining of metal ores	5	Furniture manufacturing industries	1
Other extractive industries	30	Computer and system manufacturing	0.6
Meat processing and preservation	64	Manufacturing of electrical devices	1
Fish, crustacean and molluscs processing and preservation	31	Production of bakery and starchy products	24
Fruits and vegetables processing and preservation	155	Production of other food products	24
Production of vegetable and animal oils and fats	230	Production of animal feeds	24
Dairy industry	57	Beverage industries	483
Processing of grains, production of starch and starchy products	1.5	Bar and catering services	0.4
Tobacco industries	7.5	Computers and radio industries	1
Textile industries	17	Medical devices manufacturing	0.6
Clothing packaging industries	0.6	Vehicle and means of transport manufacturing	1.7
Leather tanning industries	145[a]	Furnitures manufacturing and other manufacturing industries	1.7
Wood manufacturing industries	1.6	Recovery and recycling	0.6
Paper-mill industries	118	Energy and gas production industries	1.4
Printing industries	0.6	Water collection, purification and distribution of water	0.6
Coke and petroleum products industries	66	Chemical industries	66
Rubber and plastics industries	10	Hotel	1.1

[a] Value estimated by the authors on the base of procedure reported in AdB Tevere – Relazione Generale del Piano Stralcio del tratto metropolitano del Tevere, dal Castel Giubileo alla foce- Capitolo 2. (www.adtevere.it/note/106).

where W_i :is the total number of workers for the i-th hydro-demanding economic activity; Cf_i :is the transformation coefficient in *IE* respect to specific worker by type and the sum is done on all hydro-demanding economic activities.

The BOD_5^I in one year per municipality was calculated according to Eq. (9):

$$BOD_5^I\left(\frac{ton}{year}\right) = \frac{IE^I \cdot 60 \cdot 365}{1000000} \tag{9}$$

The eutrophication loads of phosphorus and nitrogen in one year per each municipality ($LS_{N,P}^I$) have been assessed using the coefficients Cf_N^I reported in Table 2, according to Eqs. (10) and (11):

$$LS_N^I = \frac{Cf_N^I \cdot \Sigma_i W_i \cdot 365}{1000000} \tag{10}$$

$$LS_P^I = 10\% \frac{Cf_{N,P}^{RP} \cdot IE^{RP} \cdot 365}{1000000} \tag{11}$$

4.4. Agriculture

The agriculture contribute only affects the eutrophication load. The nitrogen and phosphorous loads in one year per each municipality were calculated according to Eq. (12), using the coefficients $Cf_{N,P}^{C,U}$ reported in Table 2:

$$DS_{N,P}^{C,U} = \frac{Cf_{N,P}^{C,U} \cdot A^{C,U} \cdot 365}{1000000} \tag{12}$$

where $A^{C,U}$ is the area related to cultivated and uncultivated soil present within each municipality located in the UoM-Sarno. The extension of these areas was extrapolated by Corine Land Cover 2018 shapefile using QGIS software 3.18.1 version.

4.5. Zootechnical activities

To evaluate the zootechnical contribution to *OPL* and *EL* in one year per each municipality, ISTAT data relative to the livestock, including cows, sheep, goats, rabbits, pigs and chickens, were used (Fig. S1). The livestock values were scaled on the base of used agricultural surface in each municipality.

The IE^z were calculated using the equivalence coefficients factors reported in Table 4 according to Eq. (13):

$$IE^z = k\Sigma_i W_i^Z \cdot Cf_i^Z \tag{13}$$

where:

k : is the fraction of used agricultural surface present in each municipality; W_i^Z : is the total number of animals in the specific livestock; Cf_i^Z is the transformation coefficient respect to specific livestock; and the sum is done on all the livestock species.

The zootechnical contribution to *OPL* in one year per each municipality, was obtained by Eq. (14):

$$BOD_5^Z\left(\frac{ton}{year}\right) = \frac{IE^z \cdot 60 \cdot 365}{100000} \tag{14}$$

The zootechnical contribution to *EL* were calculated according to Eq. (15) and Eq. (16), using the coefficients $Cf_{N,P}^Z$ of Table 4:

$$DS_N^Z = \tag{15}$$

$$DS_P^Z = \frac{k \cdot 365 \cdot \Sigma_i W_i^Z \cdot Cf_{P_i}^Z}{100000} \tag{16}$$

where: W_i^Z :is the total number of animals in the specific livestock; k is the fraction of used agricultural surface present in each municipality; Cf_i^Z :is the transformation coefficient respect to specific livestock; and the sum is done on all the livestock species.

5. Results and discussion

5.1. Spatial distribution of population and population density

The population and its distribution on the territory of UoM-Sarno constitute a pressure factor of noteworthy importance, associated with the exploitation of natural resources, waste production, and the modification of the pristine environments. In Fig. S2, the population distribution from 2011 to 2018 on the 52 municipalities is shown. Over the period 2011–2018, Torre del Greco always appears to be the most populous municipality with over 80,000 inhab., followed by Castellammare di Stabia (over 60,000 inhab.) and Portici (over 50,000 inhab.). However, during the studied period, in the three municipalities the number of inhabitants decreased by 2.64 %, 1.76 %, and 3.32 %, respectively. A similar circumstance is recorded in the less populous municipality called Calvanico, where the number of inhabitants decreased from 1581 in 2011 to 1461 in 2018. As shown in Fig. 3 (i.e., the spatial distribution of RP for the year 2018 is displayed together with the spatial distribution of population density), the major RP is localized along the coastline.

The municipalities with higher population density are Portici (just under 12.000 inhab./km^2) and San Giorgio a Cremano (just above 10.000 inhab./km^2), followed by Castellamare di Stabia e Torre Annunziata with a population density >5000 inhab./km^2. The population density recorded in these towns are unique in the world, being higher than that of some of most populated cities in the word as Singapore with approximately 7800 inhab./km^2 (www.singstat.gov.sg) and London with approximately 5700 inhab./km^2 (www.ons.gov.uk).

5.2. Spatial distribution of economic activities

The economic development of the area has registered a general increase of about 6 %, passing from 70,357 activities in 2011 to 74,602 in 2018. Only 11 of 52 municipalities taken in account experienced a decrease of their own economic activities (i.e., Quindici 15.9 %, Contrada 11.1 %, Bracigliano 7.1 %, Casola 6.6 %, Castel San Giorgio 3.2 %, Pagani 2.5 %, San Giorgio a Cremano 2.3 %, Siano 2.2 %, Solofra and Torre del Greco

Table 4
Equivalent coefficients for zootechnical activities (modified by Barbiero et al., 1998).

Livestock	Cf^Z [IE]	Cf_N^Z [g N/livestock d]	Cf_P^Z [g P/livestock d]
Cows	8.16	7.51	1.01
Horses	8.08	8.49	1.19
Pigs	1.95	1.56	0.52
Sheep and goats	1.78	0.68	0.11
Rabbits	1.78	0.68	0.11
Chickens	0.20	0.07	0.02

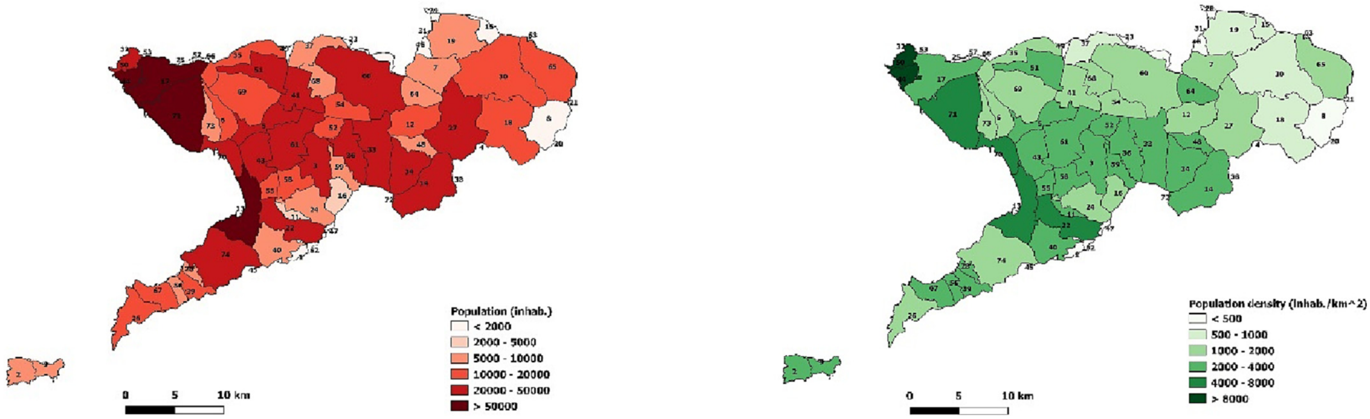


Fig. 3. Spatial distribution of population and population density per each municipality belonging to UoM Sarno.

0.7 %, and Boscotrecase 0.5 %). Except for Lettere and Calvanico, the variation of which is negligeable in the period, the others increased with a maximum value for some municipality of Sorrento Peninsula and Capri (22.7 %). In Fig. S3, the distribution of economic activities was reported per municipality from 2011 to 2018. The spatial distribution of the economic activities and the percentage of distribution for the first five principal economic categories classified in 2018 within the UoM Sarno was displayed in Fig. 4 a and b, respectively.

Torre del Greco was the municipality with the highest number of activities (4177), followed by Castellammare di Stabia (4097) and Cava de' Tirreni (3892). On the contrary, the highest number of workers was registered in Castellamare di Stabia with approximately 11,500 workers over whole the period considered, followed by Torre del Greco with an average number of workers of approximately 10,500.

Analyzing Fig. 4 b, the economic category with the higher number of activities is the wholesale and retail trade (35 %) followed by the professional, scientific, and technical activities (15 %), manufacturing activities (9 %), buildings and accommodation and catering services (both 8 %). Among the manufacturing activities, in 2018 clothing, leather and fur making ranked first with 1571 activities (23 % of the whole), followed by food industry with 1299 activities (19 %) and metallurgic industry with 898 activities (13 %). However, this distribution was quite the same also in all the other considered years. More than a third of clothing, leather and fur making is constituted by tannery activities (420 activities) mainly (72 %) localized in Solofra (upper area of UoM-Sarno).

The average number of workers employed in manufacturing activities is shown in Fig. 5a. Solofra ranked first with 2463 workers, 83 % of them working in tannery activities. In Fig. 5b, the average number of workers in food and beverage industry is shown. Angri ranked first with 941 workers, 76 % of them employed in processing and preservation of fruit and tomatoes.

5.3. Spatial distribution of organic pollution loads

Considering the resident and floating population, the economic activities and the livestock, 2,803,087 *IE* insist on the UoM-Sarno, producing about 61,400 tons BOD_5/year. A representation of the *OPL* per each municipality in 2018 is shown in Fig. 6. The highest BOD_5^{RP+FP} and BOD_5^{I} are produced by Torre del Greco, with about 1800 tons BOD_5/year and Solofra with about 6700 tons BOD_5/year, respectively. This could be quite unexpectedly since Torre del Greco and Castellammare di Stabia hosted the highest number of activities and workers, respectively. However, the OPL depended not only on the dimension of the industrial activities (number of workers), but also by the related typology. Therefore, this result was related to the highest number of workers in tannery and food and beverage industries (Fig. 5b) hosted in Solofra and Angri, respectively, to whom correspond the higher coefficients of Table 2. According to Fig. 7, where the spatial distribution of organic polluting load is shown, the highest OPL values are localized in the Sarno flatland, with the exception of Solofra that represents a *hot spot*.

5.4. Spatial distribution of eutrophication loads

Enhanced nutrient levels lead to oxygen deficits, and frequent occurrences of harmful algal blooms, finally impacting nutrient enrichment in coastal waters. Moreover, research shows that phosphorus is a limiting

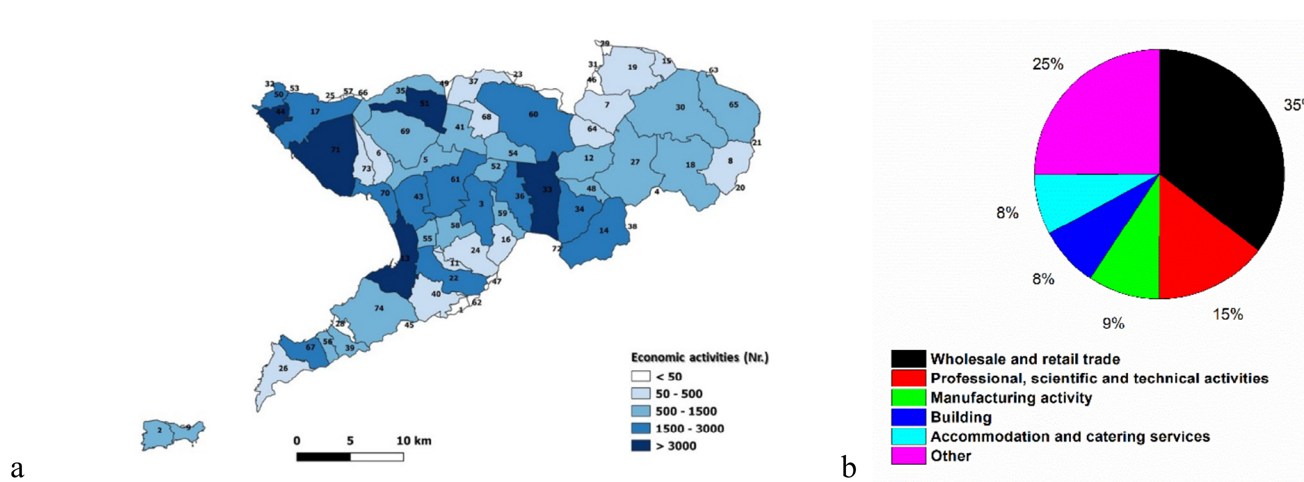
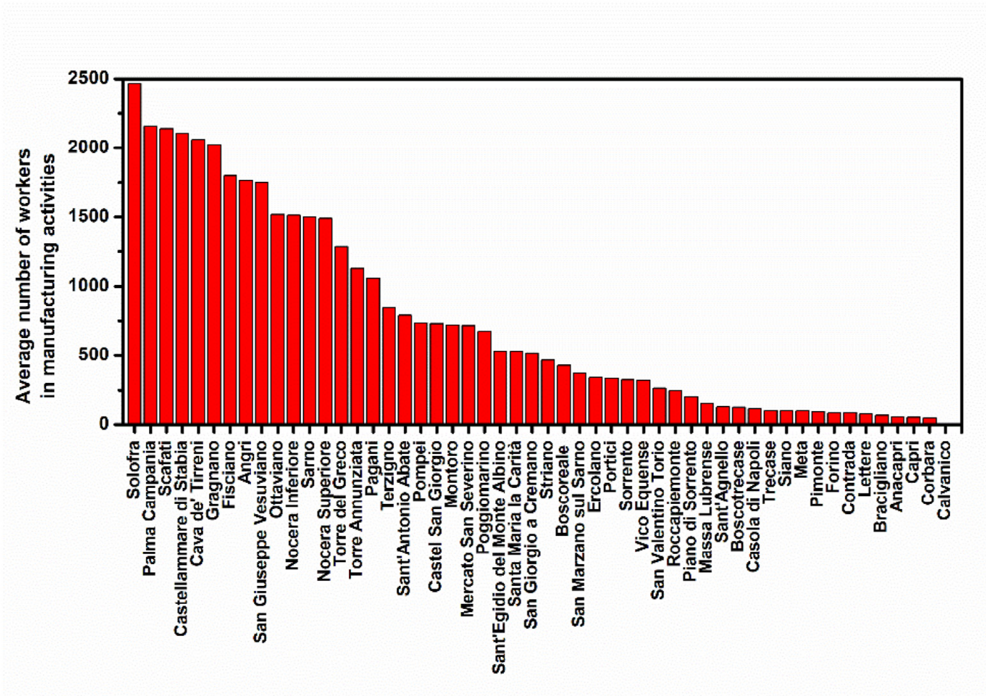
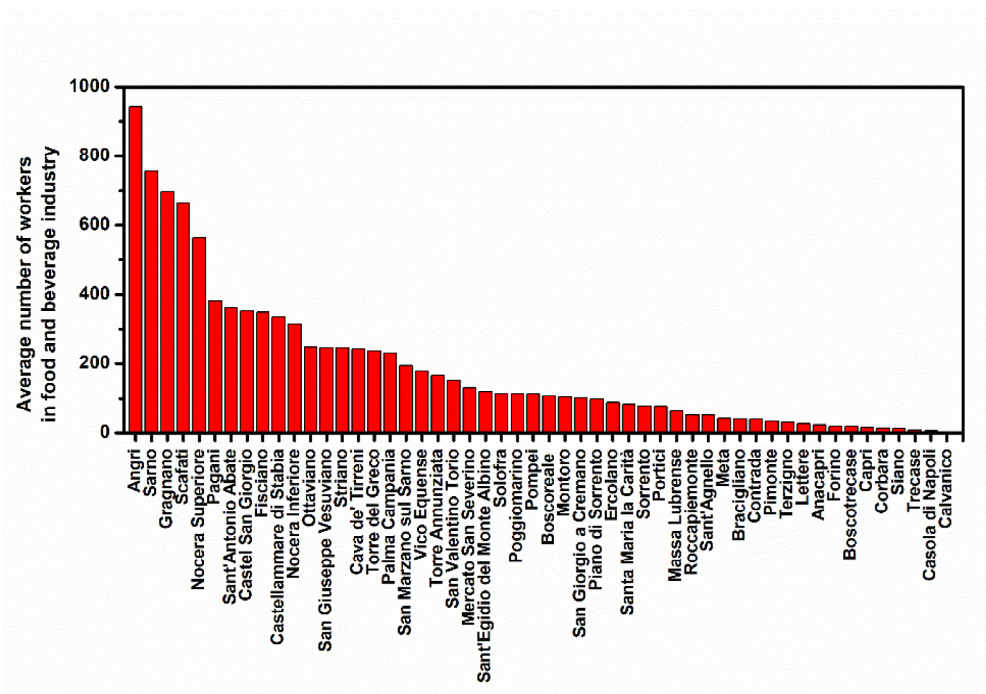


Fig. 4. a) Spatial distribution of economic activities per each municipality belonging to UoM Sarno; b) principal economic categories classified in 2018 within the UoM Sarno.



a



b

Fig. 5. Average number of workers in 2018, employed in a) manufacturing activities; b) food and beverages activities.

factor for most river ecosystems (Thomann and Mueller, 1987). The theoretical loads of phosphorus and nitrogen assessment based on the coefficients reported in Table 2 are depicted in Fig. 8. The total load is derived from the sum of the loads of diffused sources (cultivated and uncultivated soil) and localized ones (residents, tourists, industry, and livestock). Nitrogen load is mainly influenced by industrial activities and slightly from resident and floating population, the phosphorous load presented an opposite pattern. Solofra, Angri, and Scafati are the first three municipalities with the greatest nitrogen production, whereas Torre del Greco, Castellamare and Portici showed the highest values of estimated phosphorous load. The estimated phosphorus load associated with hydro-demanding activities affects the overall phosphorus load for a minimum of 4 % (Vico Equense) up to a maximum of 9 % (Portici).

From the spatial distribution of nitrogen loads on UoM-Sarno shown in Figs. 9, the load associated with the cultivated soil is fairly evenly distributed, even if it constitutes a greater pressure in the Sarno flatland. This result agrees with the regional map of nitrate vulnerability (Fig. S4) which shows how the Sarno flatland is a particularly sensitive area. The contribution of non-cultivated soil to the estimated nitrogen load is in fact negligible. The coastal municipalities and those of the Plan of Sarno determine

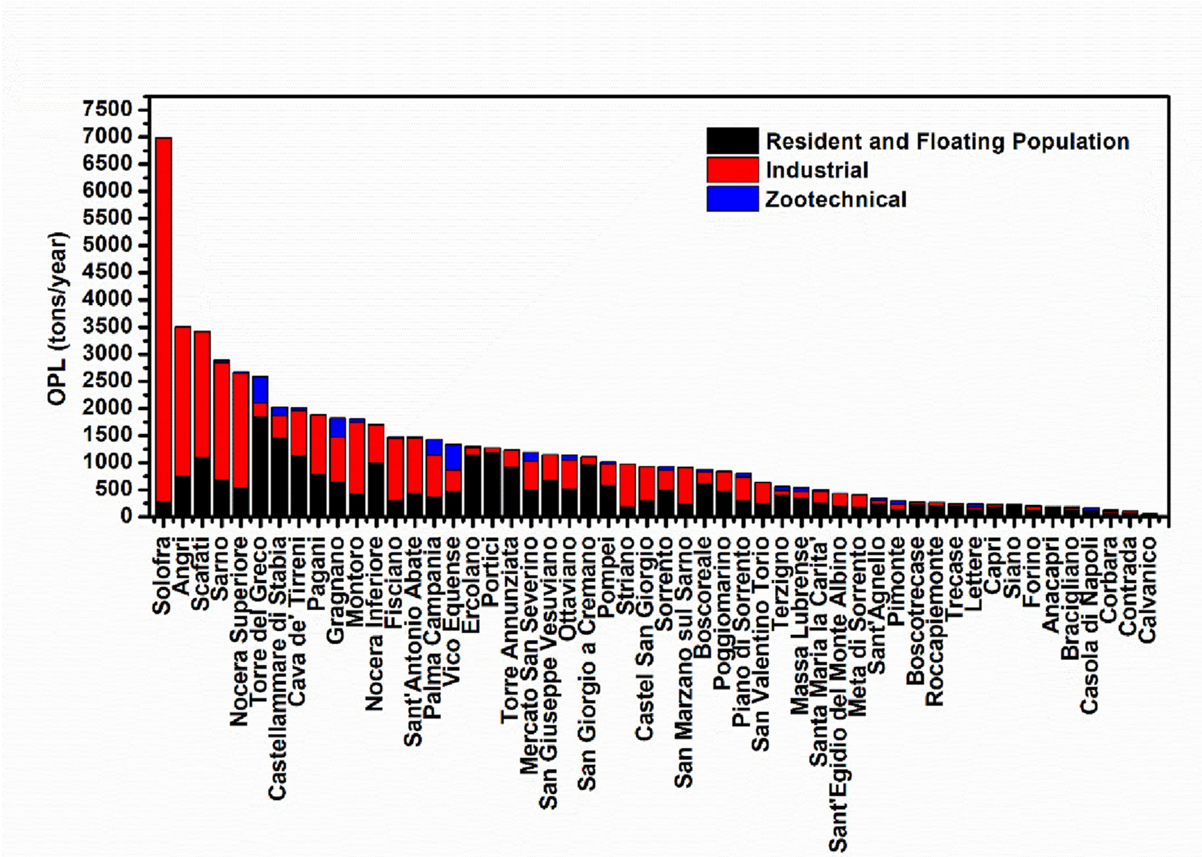


Fig. 6. Organic pollution load assessment per municipality.

the greatest contribution to nitrogen load associated with the population. With regard to the industrial contribution, there is a greater pressure associated with the municipalities of Solofra, Angri, and Scafati. The distribution of the livestock load is substantially uniform in the Sarno Plain municipalities while a greater pressure in the municipalities of the Sorrento peninsula is shown.

The estimated phosphorus load for the livestock sector affects the estimated total phosphorus load from 0.04 % (Portici) to 47 % (Casola di Napoli). In the case of cultivated soil, the estimated phosphorus load affects the total for a minimum of 0.2 % (Portici) and up to a maximum of 29 % (Palma Campania). The spatial distribution of phosphorus loads on UoM-Sarno reported in Fig. 10, showed that the highest loads are localized along the coastal municipalities and in Sarno flatland.

5.5. Evaluation of wastewater treatment plants capacity of SRB

In 1973, the Special Project 3 (SP3) sponsored by Cassa del Mezzogiorno, a public body that was created to support the development of Southern Italy, promoted the construction of several wastewater treatment plants (WWTPs) to restore good environmental conditions in the Gulf of Naples after a cholera epidemic. To date, nine WWTPs are located in the UoM Sarno, six of them named Solofra, Upper Sarno, Middle Sarno section 4, Middle Sarno section 2–3, Middle Sarno section 1 and Lower Sarno WWTPs are operating in SRB, Punta Gradelle WWTP serves the municipalities of Sorrento peninsula while Capri and Anacapri WTTPs are located in Capri Island (Fig. 11).

The whole treatment capacity of SRB WWTPs is approximately 2,300,000 IE (Table 5). All WWTPs are based on activated sludge process and characterized by preliminary treatments, primary sedimentation followed by a mixed liquor aeration tank and a final clarifier before the disinfection unit. The Solofra WWTP was designed to serve the leather tanning district, treating mainly industrial wastewater (80 %), thus a physico-chemical treatment has been included among the treatment units. The effluent of Solofra WWTP is conveyed into Middle Sarno section 4 WWTP for a further treatment. But the Lower Sarno WWTP, equipped with an underwater pipeline, all the others WWTPs discharge final effluents in canals or streams conveyed into Sarno river.

Except for the Solofra and Middle Sarno section 4 WWTPs, all other WTTPs are working below the planned treatment capacity, due the missing of sewages. The main gap in the treatment is associated to Middle Sarno section 1 WWTP that is working only at 14 % of its capacity. The whole town of Torre del Greco, which produces one of the highest OPL (Fig. 7d), delivers wastewater directly to the coastline.

Some industries have their own specialized facilities to treat wastewater to comply with the regulations regarding the discharge of treated wastewater into the riverine environment (D.Lgs. 152/06). Some others discharge partially treated or untreated wastewater to the municipal sewer system.

In order to assess the treatment capacity of WWTPs in the present configuration respect to the estimated loads, three scenarios were evaluated, considering that 80 %, 50 % and 30 % of discharges from the hydro-demanding activities could be conveyed together with domestic and zootechnical loads to WWTPs (Table 6). In the case of municipalities delivering to different WWTPs, the load was distributed according to the municipal area delivered to the reference treatment plan (Fig. 11).

If 80 % of hydro-demanding activities discharges is conveyed to WWTPs only Middle Sarno Section 4 and Lower Sarno WWTPs would be able adequate respect to the maximum capacity; the Middle Sarno Section 1 and Middle Sarno Sections 2–3 WWTPs resulted inadequate respect to the potential number of inhabitants equivalents even if 50 % of industrial discharges would be conveyed. The Middle Sarno Section 1 WWTP is still insufficient also when only 30 % of industrial discharges is assumed to be treated.

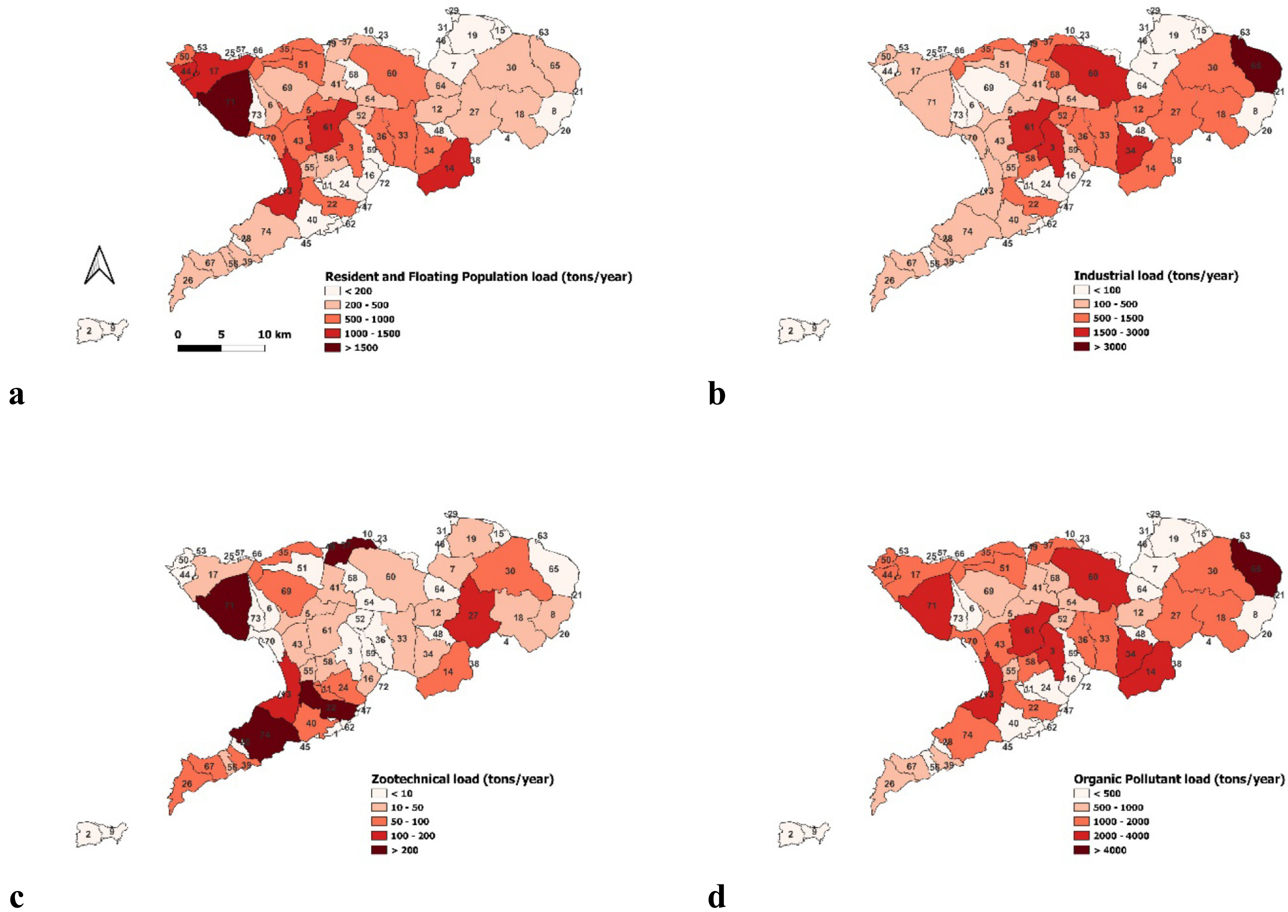


Fig. 7. Spatial distribution of OPL per each municipality belonging to UoM-Sarno (referred to 2018 data); a) Resident and Floating population load; b); Industrial load c) Zootechnical load; and d) Total organic polluting load.

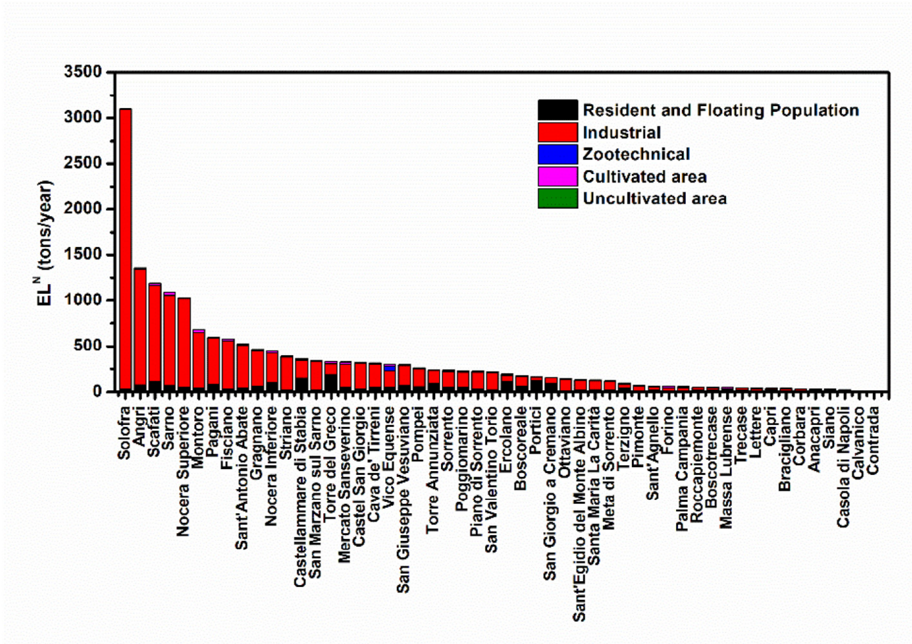
5.6. Discussion

According to our studies about 58 % of OPL is produced by industries, 36 % from resident population and 6 % from livestock. 62 %, 34 % and 3 % of industrial, domestic and livestock OPL respectively is produced in the 38 municipalities located within the SRB that represent a hot spot area within the Sarno UoM. According to Table 5, approximately 1,710,000 IE are treated, and 1,835,000 IE could be potentially treated, despite 2,310,947 IE estimated by considering resident and floating population, industries, and livestock. In addition to 2590 tons BOD/year discharged by the town of Torre del Greco not collected yet, it has been estimated that potentially other 10,600 tons BOD/year considering the contribution of population, industries, and livestock, are discharged into Sarno river reaching the sea.

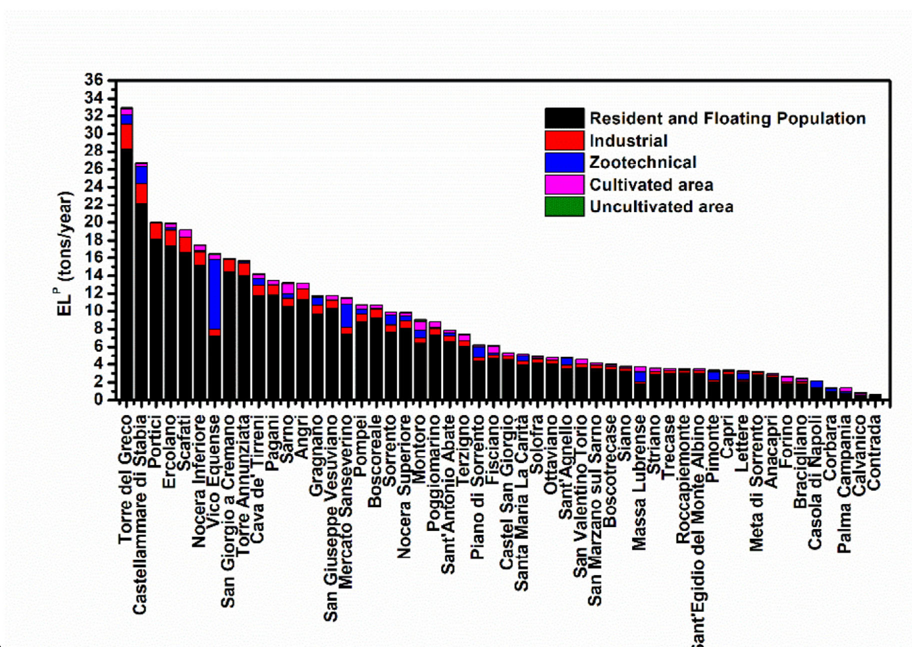
Regarding to the completion of the sewage collection system and upgrading of WWTPs of the SRB, a recent protocol was signed between the Campania Region and the company managing the water services in the area (GORI, 2020).

The concerns related to effluents originated from the industries are mainly due to chronic toxicity effects caused by the mixture of the recalcitrant compounds used in the manufacturing processes that can be released to the environment and can be long lasting also after conventional treatment (Meriç et al., 2005; De Nicola et al., 2007; Lofrano et al., 2008) or may inhibit nitrification processes into WWTPs (Jochimsen and Jekel, 1997). The EU directive 2003/53/EC restricted the marketing and use of products and product formulations used in textile and leather tanning industries that contain >0.1 % of nonylphenol ethoxylates (NPE) or nonylphenol (NP) in Europe due to its adverse effects (Carotenuto et al., 2019). However, to date no restriction has been established yet for synthetic tannins used in leather tanning industry with their complex structure composed of a mixture of chemicals. Based on our previous experience, synthetic tannins are characterized by a very low biological treatability (BOD_5/COD <0.2), acute and chronic toxicity (Lofrano et al., 2007, 2008) and are able to inhibit the nitrification processes. Moreover, as shown in Fig. 5b the agroindustry, that represents an important field of Sarno river basin economy, can contribute to create a further stress to WWTPs since its discharge can cause flow rate variation ranging from one third to the double of the average flow rate. A part of this water could be usefully reused to reduce the pressure on centralized WWTP and to match the new EU regulation on water reuse (Regulation (EU), 2020/741) which will be in force from June 2023.

A proper management of wastewater from livestock farms is also necessary due to its environmental impact. The uncontrolled dumping of livestock wastewater is particularly important since can contribute to nitrate discharge into the aquifers and soils in an area that has already been classified vulnerable to nitrate (Directive 91/676/EEC on the protection of water against pollution by nitrates from agricultural sources). Besides its high concentrations of nitrogen, phosphorus and organic matter (Ramankutty et al., 2018), these wastewaters are even more characterized by the presence of contaminants of emerging concern such as antibiotics and their discharge into WWTPs can contribute to make them hot spot of such kind of contamination. It could be evaluated the implementation of a natural/decentralized WWTPs at individual farm scale as an alternative to the conventional treatment systems used in centralized, large-scale facilities with



a



b

Fig. 8. Assessment of a) nitrogen and b) phosphorus loads.

the advantages of low energy costs, high capacity for the elimination of contaminants, and the achievement of an adequate reuse of the effluent (Mendieta-Pino et al., 2021).

The goal of environmental sustainability should be pursued to reduce reliance on discharge dilution phenomena and maximise treated wastewater reuse and by-products recovery (Libralato et al., 2012). The chance of creating a green deal in Sarno river basin requires: i) more sustainable industry processes which look for the adoption of green procedures and chemicals and the updating of WWTPs with processes able to degrade bio recalcitrant organic pollutants to harmless compounds for human health and the environment; ii) more sustainable water uses from hydro-demanding activities; iii) the completion of the sewage system and updating of WWTPs; iv) governing the territory in order to restore and safeguard the potentiality of the area.

6. Conclusions

The present study allowed to investigate and identify the state of anthropogenic pressures over the entire territory of UoM-Sarno, in particular, focusing onto the area of the Sarno river basin. Besides the Solofra district which constitutes a hot spot of industrial pressure on the territory, the Sarno flatland is characterized by the widespread presence of hydro-demanding manufacturing activities and by a very high population density for some municipalities that can be considered as unique around the world. The analysis of the organic load showed a highest distribution in the municipalities of the Sarno flatlands and in the coastal municipalities, rather than in the mountain municipalities, except for the municipality of Solofra. The domestic and industrial components of wastewater have a significant different impact on the total load for the single municipalities, being mainly

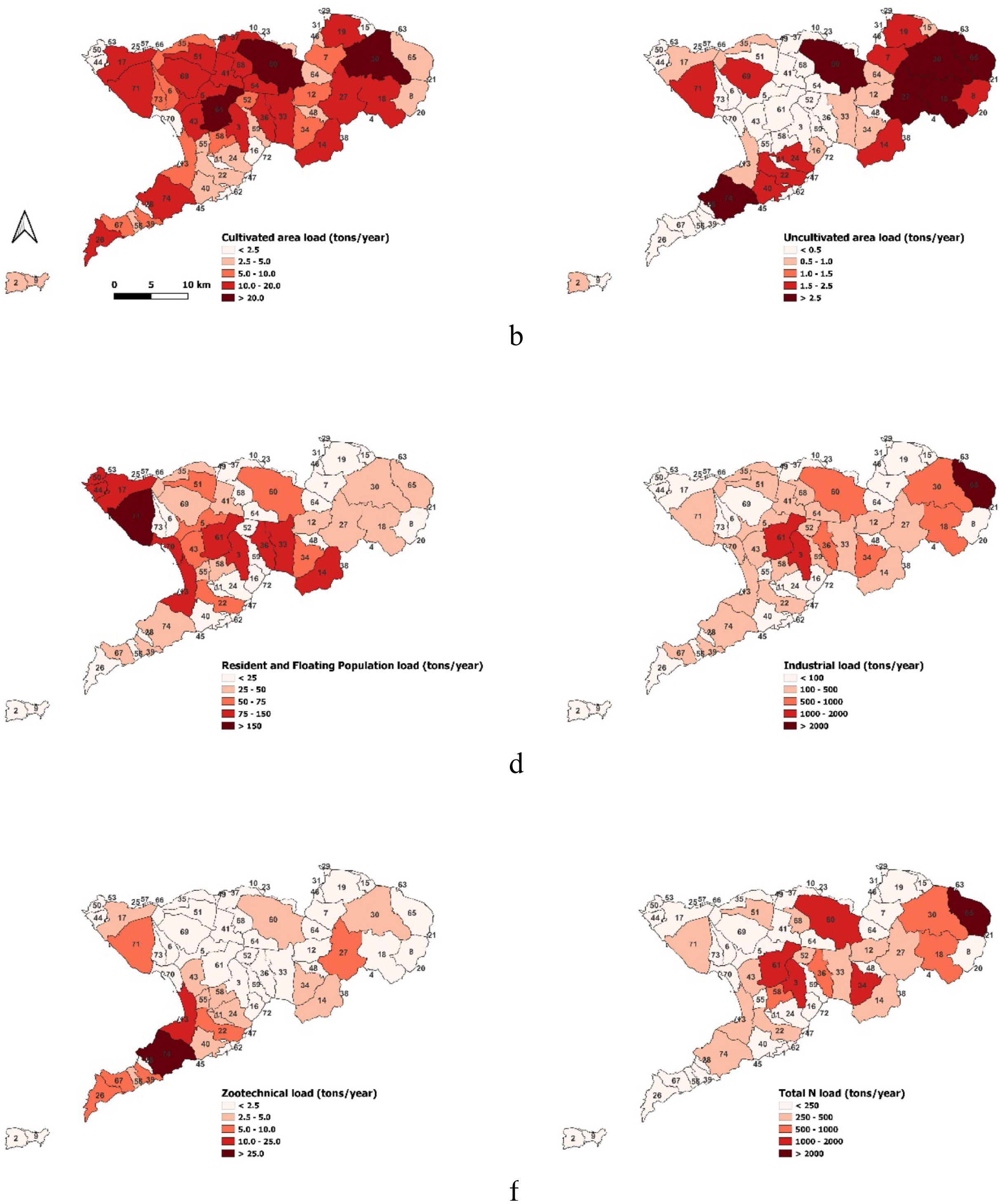


Fig. 9. Spatial distribution of nitrogen load per each municipality belonging to UoM-Sarno. a) Cultivated area load; b) Uncultivated area load; c) Resident and floating population load; d); Industrial load e) Zootechnical load; and f) Total nitrogen pollution load.

attributable to a high population density on the coast and to the presence of hydro-demanding activities in the Sarno flatland. From the analysis of the eutrophicating loads, it emerged that the load associated with the cultivated soil is fairly evenly distributed and constitutes a greater pressure in the Sarno flatland, however not significant compared to the other considered sources. The spatial distribution of the eutrophication load associated with the livestock sector is substantially uniform in the municipalities of the Sarno flatlands and determines a greater pressure in the coastal areas. Such results can be used for the integrated management of the SRB, providing a database supporting the potential definition of the measures to be implemented for the environmental protection and restoration of the UoM-Sarno, including the upgrading of the existing wastewater treatment plants.

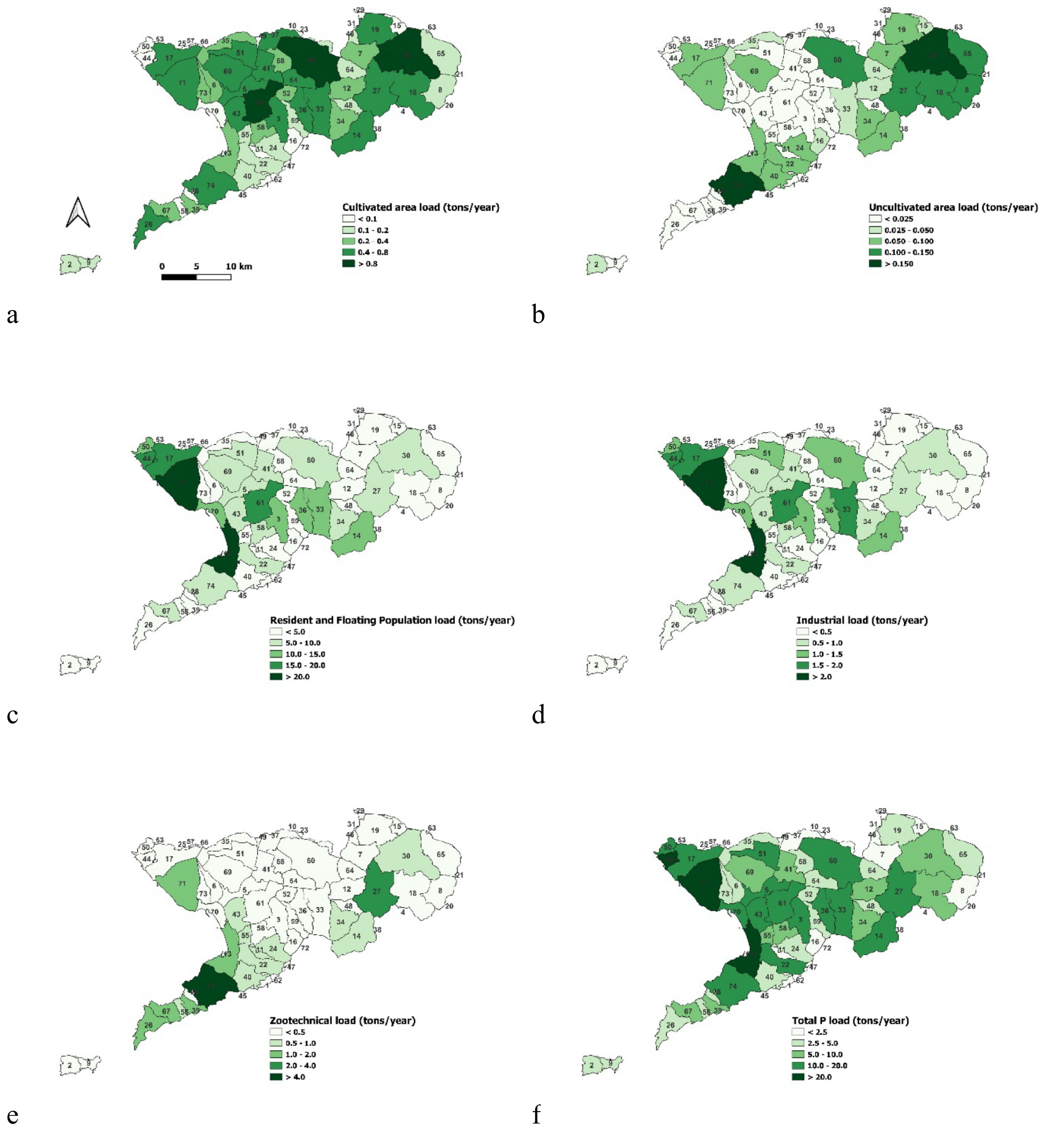


Fig. 10. Spatial distribution of phosphorous load per each municipality belonging to UoM-Sarno. a) Cultivated area load; b) Uncultivated area load; c) Resident and floating population load; d); Industrial load e) Zootechnical load; and f) Total phosphorous pollution load.

CRediT authorship contribution statement

- Giusy Lofrano: Investigation; Conceptualization, Writing - Original Draft;
- Sara Serafini: Data curation; Formal analysis;
- Lorenzo Saviano: Data curation; Formal analysis;
- Maurizio Carotenuto: Validation; Writing - Review & Editing;
- Marco Guida: Review & Editing
- Vincenzo Romano Spica: Review & Editing
- Alice Cardito: Data curation; Formal analysis
- Giovanni Libralato: Methodology; Supervision; Review & Editing;

Data availability

Data will be made available on request.

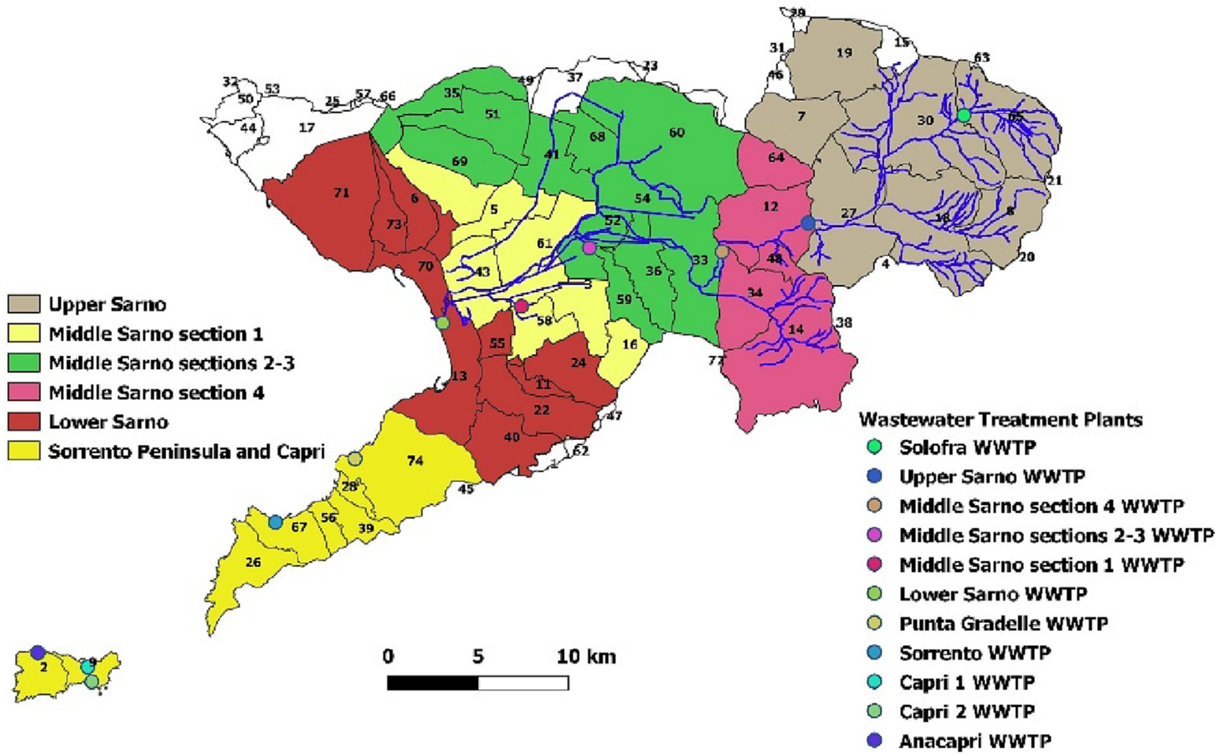


Fig. 11. Localization of WWTPs and related served area on UoM-Sarno.

Table 5
Information on WWTPs located in SRB; IE = inhabitant equivalent.

WWTPs	Maximum capacity (IE)	Actually treated (IE)	Municipalities collected
Solofra	450,000	450,000	–
Upper Sarno	200,000	182,488	Solofra WWTP, Solofra, Montoro, Forino, Mercato S. Severino (Western part), Calvanico, Fisciano, Bracigliano
Middle Sarno section 4	303,381	300,000	Nocera Superiore, Roccapiemonte (Western part), Castel S. Giorgio, Mercato S. Severino (Western part), Siano, Cava de' Tirreni (Northern part)
Middle Sarno section 2–3	472102* 308,157	278,094	Angri, Corbara, S. Egidio Monte Albino, Pagani, Nocera Inferiore, S. Marzano sul Sarno, Terzigno (Northern part), Poggiomarino, S. Giuseppe Vesuviano, Ottaviano, Sarno, S. Valentino Torio, Striano
Middle Sarno section 1	363,632	51,817	Scafati, Pompei, Terzigno (Southern part), *S. Antonio* Abate, Angri (Northern part), Boscoreale (Eastern part), Angri (163,945 EI)
Lower Sarno	518,000	445,000	Castellammare di Stabia, Gragnano, Casola di Napoli, Lettere, Pimonte, *S. Maria* la Carità, Torre Annunziata, Trecase, Boscotrecase, Boscoreale (Western part), Torre del Greco (not collected yet)

* 472,102 IE will be conveyed to preliminary treatments, 308,157 IE will be further treated in the same WWTP, the remaining 163,945 IE will be conveyed to Middle Sarno section 1 WWTP.

Table 6
Assessment of Wastewater Treatment Plants capacity located in Sarno River Basin according to three scenarios (80 %, 50 % and 30 % of IE^{I}): Green = estimated IE are lower than IE maximum capacity of WWT; Red = estimated IE are greater that IE maximum capacity of WWT; IE = inhabitant equivalent.

	IE maximum capacity	IE^{Tot} (IE^{I} 80%)	IE^{Tot} (IE^{I} 50%)	IE^{Tot} (IE^{I} 30%)
Solofra	450000	308730	308730	308730
Upper Sarno	200000	222809	180584	152435
Middle Sarno Section 4	303381	217404	171327	140608
Middle Sarno Section 2-3	308157	450703	322079	236329
Middle Sarno Section 1	363632	484166	417586	373199
Lower Sarno	518000	416730	384627	363226

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163784.

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