PM emissions from a BR basin and impact assessment on air quality

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Abstract

The article deals with the emission of fugitive dust from a major BR (Bauxite Residue) basin located in the south-west of Sardinia, where the prospect of a change in the storage practices is likely to cause the increase of PM (Particulate Matter) pollution in the surrounding region. In fact, other natural and anthropic sources already provide a variable contribution in terms of airborne dust concentration in the same territory. In accordance with the procedures established by the Directive 2011/92 (EIA Directive - *Environmental Impact Assessment*), the data recorded by a monitoring network located in the Sulcis-Iglesiente sub-region has been taken into consideration in order to define the *ante-operam* condition of the potential impact area. The additional contribution of the red mud basin has been simulated with the atmospheric dispersion model proposed by US EPA (Environmental Protection Agency). The expected whole concentration of the PM10, which includes both the pre-existing sources and the additional contribution of the red mud basin, has been estimated and compared with the limit values established by the Directive 2008/50/EC (*Ambient air quality and cleaner air for Europe*).

Keywords

Tailing basins, red mud, bauxite residue, fugitive dust emission, air quality, PM10.

1 Introduction

The red mud is the main residue of the bauxite treatment for the production of alumina (Bayer process). The main red mud disposal methods are marine disposal, lagooning, dry stacking and dry disposal [1]. Prior to the 1970s, only marine discharge and lagooning were commonly in use. From the 1970s onwards, the rapid expansion of the alumina industry, the ever-increasing public awareness about environmental problems, as well as the implementation of progressively more restrictive environmental protection standards, led to the progressive conversion from wet to dry disposal practises (such as dry stacking and dry disposal) [2, 3]. The dehydration treatment of the processing residue prior to disposal causes in fact the reduction at source of pollution hazards for underground soil and water, due to the substantial reduction of the mud lechability [4]. On the other hand, the conveyance of the dried residue from the filtration plant to the basin, the disposal operations within the basin area and the succeeding action of the wind upon the exposed basin surfaces may cause the emission of fugitive dust in the surrounding area, with a potential increase of PM10 (particulate fraction with a cut diameter of 10 micrometres) air concentration. The article discusses the issue with reference to a red mud basin located in the industrial area of Portovesme, in the south-west of Sardinia, where the prospect of a change in the storage practices, from lagooning to dry disposal, is expected to favour the re-start of the alumina production in the only refinery currently operating in Italy [5].

The study of the dust dispersion phenomenon has been carried out by means of the CALPUFF modelling system, the code suggested by US Environmental Protection Agency (US EPA). The data recorded by the air quality-monitoring network located in the Sulcis-Iglesiente sub-region has been considered to

define the *ante-operam* condition of the potential impact area under investigation, in accordance with the procedures established by the Directive 2011/92 (EIA Directive - *Environmental Impact Assessment*) [6].
The expected whole concentration of the PM10, which includes both the pre-existing sources and the additional contribution of the red mud basin, has been estimated and compared with the limit values established by the Directive 2008/50/EC (*Ambient air quality and cleaner air for Europe*) [7].

2 The case study

2.1 The Portovesme red mud basin

The red mud basin under consideration is located in southern Sardinia (Italy), within the industrial area of Portovesme (Figures 1). Since the 1970s the residue of the bauxite treatment has been disposed by lagooning. Considering the geographic location of the basin and the related meteo-climatic variables (rain and evaporation rate), the prospect of adding new embankments over the existing basin would require the constraint of the embankments vertical growth to a limit of 1 m/y, in order to allow the consolidation of the previously disposed mud up to a 65% solid content.
The currently available evaporating surface (84.8 ha) combined with the limit elevation rate of 1 m/y would establish a maximum dischargeable volume of 850,000 m^3/y, corresponding to a maximum alumina outcome of 1,580,000 t/y. In four years' time, the total evaporating surface would be reduced to 66.4 ha, the maximum dischargeable volume would be 664,000 m^3 and the alumina production rate would be no more than 1,230,000 t/y, with possible negative effects in terms of overall economic result for the alumina company. In this perspective, also considering the unavailability of land and the environmental impacts associated to the hypothesis of a new basin, it has been decided to use the existing basin by changing the disposal practises from lagoonig to dry disposal [8].
The plan implies the construction of a filtration plant, to enable the dehydration of the bauxite-processing residue up to a 70% solid content. Once dried out, the residue would be loaded into dumpers and transferred to the basin summit, to be spread and rolled with traditional earth-moving machinery. That solution puts together the company economic interest and a global minor impact on the environment, both during the alumina processing phase and afterwards (post-closure).

Figure 1: Location of the basin within the industrial area of Portovesme (Sardinia)

As regards the operation of the landfill, in particular, the disposal of a dried residue will allow to overcome the limit superimposed by the residue consolidation velocity, as it eliminates the association between the annual outcome of alumina and the areal extent of the evaporation surface. In addition, the disposal of a dried residue removes the need for the construction of additional upper embankments, with a consequent constriction of the enterprise costs. From the environmental point of view, the prior removal of most of the liquid phase from the processing residue attenuates the potential hazard of underground and underwater contamination, which only remains dependent on the moisture content of the previously disposed mud.

On the other hand, the construction activities needed to adapt the basin and support the new disposal practices, the disposal activities (loading, transportation and placement of the dried residue), as well as the formation of wide surfaces of disposed material exposed to wind, may generate significant emissions of fugitive dust with possible increase of air contamination in the surrounding area. That issue is widely discussed in the following part of the article, starting from the analysis of the elementary working phases contemplated in the basin conversion project.

2.1 The basin conversion project

Since the 1970s, the residue of the bauxite treatment has been disposed by lagooning in three sectors of the basin (A, B and C in Figure 2). The two main sectors A and B are 26 m high and occupy 114 ha of land; they have been developed according to the up-stream method and presently consist of a 10 m high lower embankment and 9 secondary embankments, which give the basin its truncated-pyramidal current shape. The sector C is relatively recent and therefore composed by the base embankment and only one secondary embankment, it covers 44 ha of land and is 11.5 m high.

The basin conversion project includes a variety of preliminary operations necessary to adapt the existing three sectors of the basin to the technical requirements of the EU Directive on the landfill of waste and to prepare an additional disposal area towards the north for the enlargement of the basin (new sector D). Figure 3 represents the current configuration of the basin (with the three existing sectors A, B and C) and the new sector D.

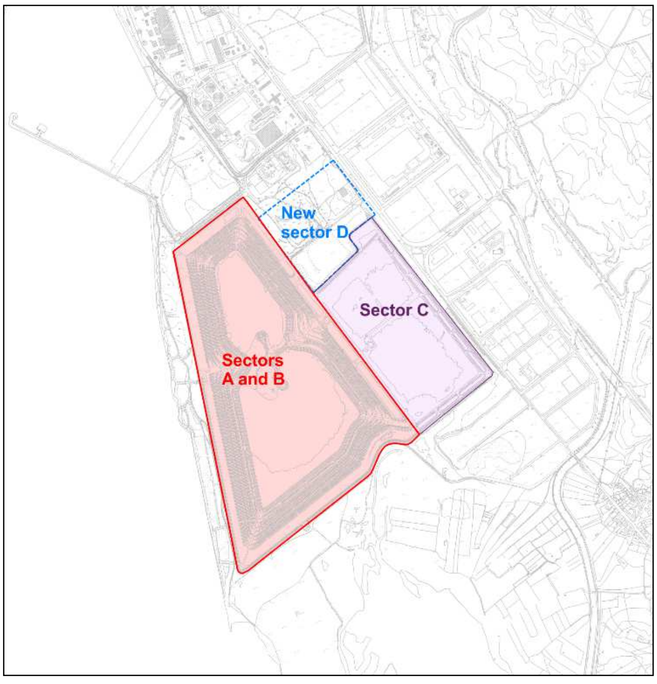

Figure 2: BR basin current configuration and hypothesis of expansion (Sector D)

The conversion project is composed of a construction stage (construction of filtration plant and decant pond; bottom insulation of sector D; *mud farming* in sector A and B) and a landfill operation stage (disposal of the dried residue above the three existing sectors A, B and C and on the new sector D).
As regards the landfill operation, in particular, the project contemplates:

- the elevation of sector C from the present level up to + 26.5 m a.s.l. (which corresponds to the current level of sectors A and B);
- the elevation of sector D up to + 26.5 m a.s.l.;
- the simultaneous raise of the four sectors (A, B, C and D) up to + 44.0 m a.s.l.;
- the final capping to the final high of + 46.0 m a.s.l..

The elementary activities included in the project are organized into five consecutive phases reported in Table 1 (numbered from 0 to 4). For the elementary activities with a potential for emitting fugitive dust, the emission factors have been calculated according to the appropriate algorithms suggested by US EPA and used as input data in the modelling of the pollution scenario associated to each phase of the conversion project reported in Table 1.

Table 1: Plan of the conversion project

Phase code	***Duration***	***Elementary activity***	***Site***
Phase 0	2 years	Construction of filtration plant	Sector D
		Construction of decant pond	Sectors A and B
		Mud farming	Sectors A and B
Phase 1	6.3 years	Red mud disposal	Sector C
		Mud farming	Sectors A and B
		Bottom insulation	Sector C
Phase 2	4.2 years	Red mud disposal	Sector C
		Mud farming	Sectors A and B
Phase 3	14.6 years	Red mud disposal	Sectors A, B, C and D
Phase 4	3 years	Final capping	Sectors A, B, C and D

3 The PM impact assessment procedure

In accordance with the procedures established by Directive 2011/92 (EIA Directive - *Environmental Impact Assessment*), the impact on any environmental component is evaluated on the basis of the pre-existing status of the component itself, before the accomplishment of the work activities proposed in the project (*ante operam* or pre-construction state). Data about the *ante operam* state of the environment is sometimes provided by public or private monitoring systems: in the case study under consideration, the public air quality-monitoring network installed by RAS (Regione Autonoma della Sardegna) in the Sulcis-Iglesiente sub-region. The additional contribution of the red mud basin to air pollution is calculated in this study by means of the CALPUFF modelling code. The expected whole concentration of the airborne dust, which accounts both for the pre-existing sources and for the BR basin, is thus compared with the limit values established by the Directive 2008/50/EC on *Ambient air quality and cleaner air for Europe*. The Directive 2008/50/EC establishes the limit values of PM10 concentration for one day (50 $\mu g/m^3$, not to be exceeded more than 35 times a calendar year) and for a calendar year (40 $\mu g/m^3$); both limits have been in force since the 1st of January 2005. As regards the PM2.5, the same Directive only establishes the limit value for a calendar year to be met by 2015 (25 $\mu g/m^3$) and one to be met by 2020 (20 $\mu g/m^3$). The analyses of the present study only refer to the coarser fraction (PM10).

3.1 The background air quality

The data recorded by the air quality monitoring system of ARPA (Environmental Protection Agency of Sardinia) has been considered to define the ante-operam condition of the impact area under investigation. Figure 3 represents the location of the four sampling stations under consideration (CENPS 2, CENPS 4, CENPS 6 and CENPS 7) and shows that CENPS 6 and CENPS 7 account for the air quality in Paringianu and Portotorres respectively. The air concentration values of PM10 (annual mean, number of exceedances of the daily limit value in a calendar year and 90.4th percentile of the daily mean) are reported in Table 2, for the 2006 – 2013 period [9]. It is worth noting that the 90.4th percentile of the daily mean corresponds to the 36th highest daily mean recorded over a year.

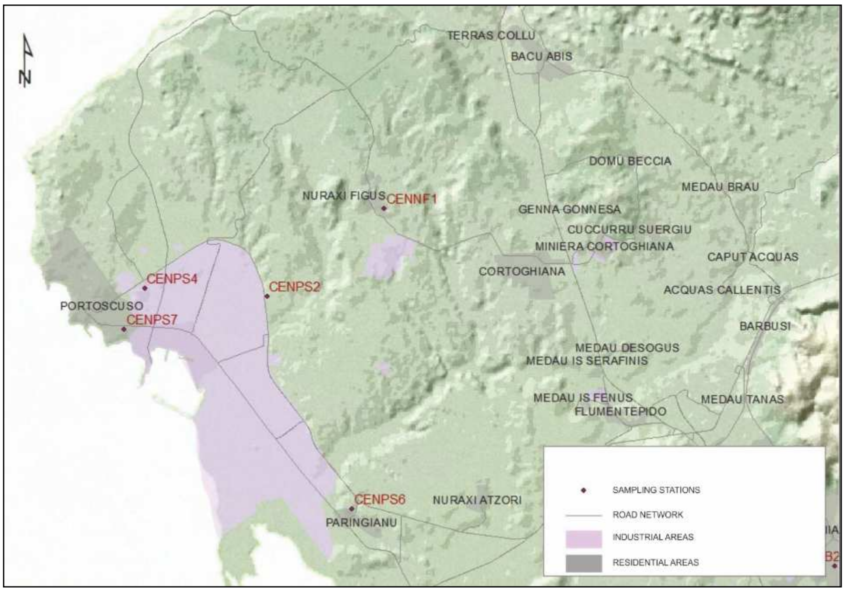

Figure 3. Location of sampling stations CENPS 2, CENPS 4, CENPS 6 and CENPS 7. Air quality monitoring system of ARPAS (Environmental Protection Agency of Sardinia).

Table 2. PM10 background air quality from 2006 to 2013 [9]

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**
Annual mean [μg/m^3]									
CENPS2	27.7	24	17	30.4	28.6	34.5	34	31.5	28.46
CENPS4	18	20	20.8	22.6	23	24.8	24.4	22.1	21.96
CENPS6	15.6	13	12.9	27.5	23.7	23.7	16.4	15.3	18.51
CENPS7	32.8	24.6	24.2	27.8	28.5	26.2	23.1	23.6	26.35
Number of exceedances of the daily limit [50 μg/m^3]									
CENPS2	16	4	1	21	9	27	24	12	-
CENPS4	-	3	12	7	5	10	6	4	-
CENPS6	-	-	-	12	3	10	2	-	-
CENPS7	38	11	11	12	16	8	1	3	-
90.4th percentile of the daily mean [μg/m^3]									
CENPS2	n.a.	n.a.	28.63	46.09	41.99	48.37	47.55	45.00	45.34
CENPS4	28.46	26.74	33.69	33.94	33.69	35.61	35.95	34.10	32.77
CENPS6	22.95	20.93	20.68	40.46	35.08	35.82	22.97	21.11	26.06
CENPS7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-

n.a. = *not available*

3.2 The emission factors

As mentioned before, for each elementary activity with a potential for emitting fugitive dust, the emission factors used to simulate the dispersion phenomenon have been calculated according to the algorithms suggested by US EPA (AP-42 Compilation of Air Pollutant Emission Factors) [10]. Table 3 reports the emission sources taken into account in this study and the corresponding US EPA emission factors for the PM10 fraction.

It is worth noting that each elementary activity in the five phases of the project (see Table 1) includes one or more emission sources (i.e.: the emission factor for each elementary activity results from the sum of a variable number of emission factors, corresponding to the number of emission sources in the activity). Each source is characterized by parameters that depend both on the work organization (type and model of moving machinery, vehicle speed, etc.) and on the site condition (silt content of unpaved roads, moisture content of material to be moved, mean wind speed in the area, etc.). All those parameters have been accurately taken into account in the calculation of the emission factors specified in Table 3.

Table 4 indicates the total duration of each elementary activity, the duration of the daily work shift, the hourly emission rate corresponding to the simulation scenario 1 (without emission control measures) and the reduced hourly emission rate corresponding to the simulation scenario 2 (with emission control due to watering of unpaved travel surfaces and Sector D bottom barrier). The value of the emission rates reported in Table 4 are based on the project plan and timetable: km travelled per year (by vehicle used for transportation), Mg of material moved per year (construction material), etc. The data in table 4 shows that the most severe condition is represented by sub-phase 1-C, which has been considered in the following simulations of PM10 dust dispersion (scenarios 1 and 2).

Table 3. Emission sources and corresponding US EPA PM10 emission factors [10]

Emission source	***EPA AP42 code***	***PM10 Emission factor***	***Equation parameters***
Material transport with dumpers	13.2.2 Unpaved road	$E = k \cdot \left(\frac{s}{12}\right)^{a} \cdot \left(\frac{W}{3}\right)^{b} \cdot 291.8$ [kg/km]	s: silt content (%) W: vehicle weight [Mg] a = 0.9 b= 0.45 k= 1.5
Material dumping with dumpers Material handling with loader	13.2.4 Aggregate Handling and Storage Piles	$E = k \cdot 0.0016 \cdot \frac{\left(\frac{u}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}}$ [kg/Mg]	u: mean wind speed (m/s) M: moisture content (%) k = 0.35
Material placing with motor grader	13.2.3 Heavy Construction Operations - Grading equation Tables 11.9-2	$E = 0.0056 \cdot 0.6 \cdot (S)^{2.0}$ [kg/km]	S: mean vehicle speed (km/h)
Material rolling with dozer	13.2.3 Heavy Construction Operations - Dozer equation in Tables 11.9-2	$E = \frac{0.45 \cdot (s)^{1.5}}{(M)^{1.4}} \cdot 0.75$ [kg/h]	s: silt content (%) M: moisture content (%)
Wind erosion from exposed surface	SPPC 1983 - Appendix A Section 1.1.17 to 1.1.18	*E=0.2* [kg/ha/h]	Exposed surface (sector D)=15.8 ha

Table 4. Elementary activities in the project and corresponding emission rates

Phase code	***Elementary activitiy***	***Phase duration [years]***	***Daily work shift [h]***	***Emission rate [kg/h]***	***Reduced emission rate [kg/h]***
0-A	Decant pond and filtration plant embankments construction	0.14	8	46.55	11.49
0-B	Decant pond embankment construction	0.86	8	44.12	9.93
1-A	Mud disposal and side capping in Sector C	4.3	12	82.02	17.33
1-B	Mud disposal and side capping in Sector C - Groundwork of Sector D	0.4	12	82.69	18.00
1-C	Mud disposal and side capping in Sector C – Bottom barrier construction in Sector D – Wind erosion from bottom barrier in Sector D	0.6	12	116.19	27.81
1-D	Mud disposal and side capping in Sector C - Embankment construction in Sector D - Wind erosion from bottom barrier in Sector D	1	12	92.86	19.86
2	Mud disposal and side capping in Sector D	4.2	12	44.08	9.74
3	Mud disposal and side capping in Sectors A B, C and D	14.6	12	104.97	21.92
4	Final capping	3	8	81.19	17.58

3.3 The air dispersion modelling

The study of the dust dispersion phenomenon has been carried out by means of the CALPUFF model system, developed by Sigma Research Corporation (currently part of Earth Tech. Inc.), with the contribution of the California Air Resources Board (CARB) [11].

The CALPUFF model system includes three main components: the meteorological processor (CALMET), the dispersion model (CALPUFF) and the post-processing code (Calpost). Figure 4 shows the flow diagram of the CALPUFF Model code, where:

- CALMET is a meteorological processor that develops hourly wind and temperature fields on a three-dimensional modelling domain. Two-dimensional fields of other variables, such as turbulence and mixing height, are also included in the CALMET output files.
- CALPUFF is a not stationary dispersion model that advects *puffs* of material emitted from modelled sources, simulating dispersion and transformation processes along the way. In doing so it typically uses the fields generated by CALMET, or as an option, it may use simpler non-gridded meteorological data much like existing plume models. Temporal and spatial variations in the meteorological fields selected are explicitly incorporate in the resulting distribution of puffs throughout a simulation period. The primary output files from CALPUFF contain either hourly concentrations or hourly deposition fluxes evaluated at selected receptor locations.
- CALPOST is post-processing code that uses the output files from CALPUFF and produces tabulations that summarize the results of the simulation, identifying, for example, the 36th highest concentrations at the selected receptors.

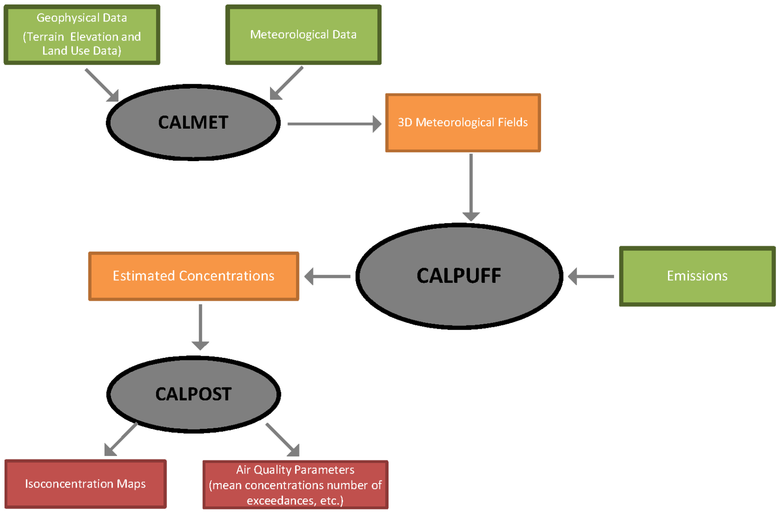

Figure 4. The *CALPUFF flow chart*

The meteorological input data considered in this study originates from LAMA (Limited Area Meteorological Analysis) dataset and refers the geographical coordinates 447.466 km Est, 4342.977 km North (WGS84 Zona 32), which identify a point in the vicinity of the emission source under investigation. The meteorological data refers to 2007, as that year better represents the historical wind data for the impact area under exam. Figure 5 represents the comparison between the wind frequency data simulated by CALMET at 10 m a.s.l. and that measured by the weather station in Carloforte at ground level. Both the wind rose of CALMET and that of the local station in Carloforte show the North-West (*maestrale*) and EST as dominant wind directions, with higher frequencies in the first case.

The modelling domain is represented in Figure 6: it has sides of 20 km; it is centred in the emission source and includes the two nearest villages of Paringianu and Portoscuso, respectively at 800 m and 3 km. The four monitoring stations (CENPS 2, CENPS 4, CENPS 6 and CENPS 7) used to define the background quality of the air are also located within the modelling domain.

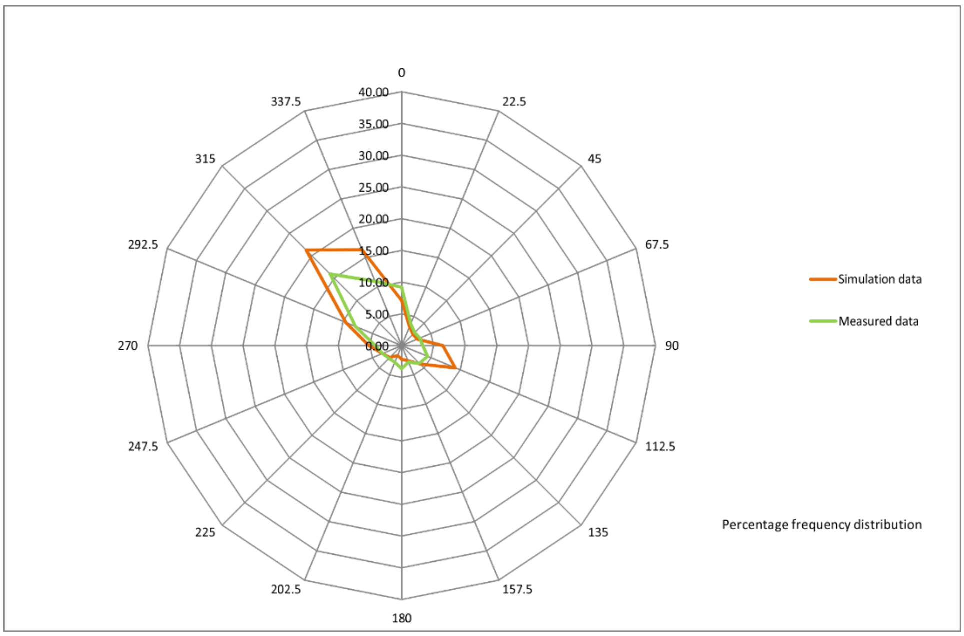

Figure 5. Simulated and measured wind frequency [%]

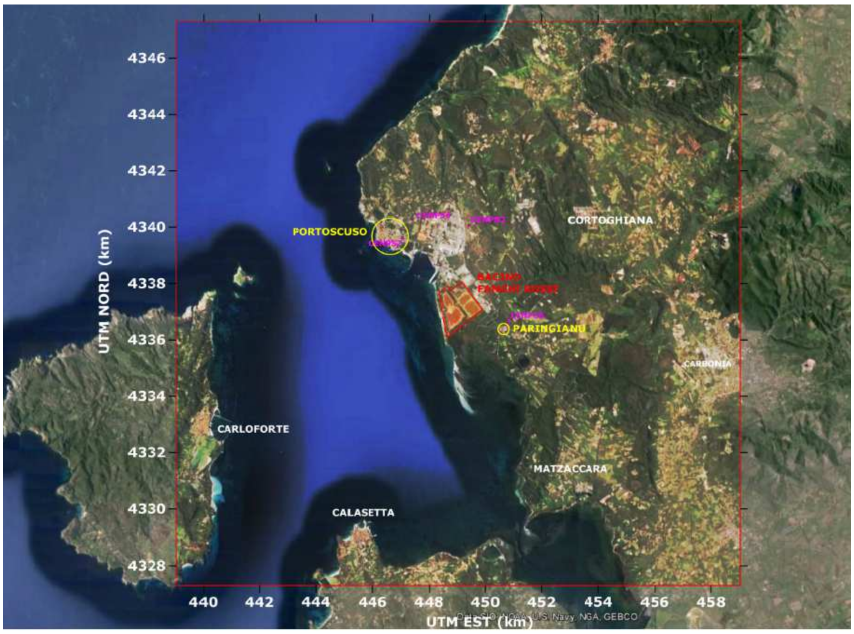

Figure 6. Modelling domain

The simulation results elaborated by CALPOST are graphically represented from figure 7 to 10, by the PM10 isoconcentration maps. In particular, the maps in figure 7 and 8 represent the isoconcentration curves of the annual mean, respectively for *scenario 1* (without emission reduction measures) and *scenario 2* (considering the contribution of unpaved travel surfaces and Sector D bottom barrier watering). The maps in figure 9 and 10 represent the isoconcentration curves of the 90.4th percentile of the daily mean (i.e.: the 36th highest daily mean) respectively for *scenario 1* and *scenario 2*.

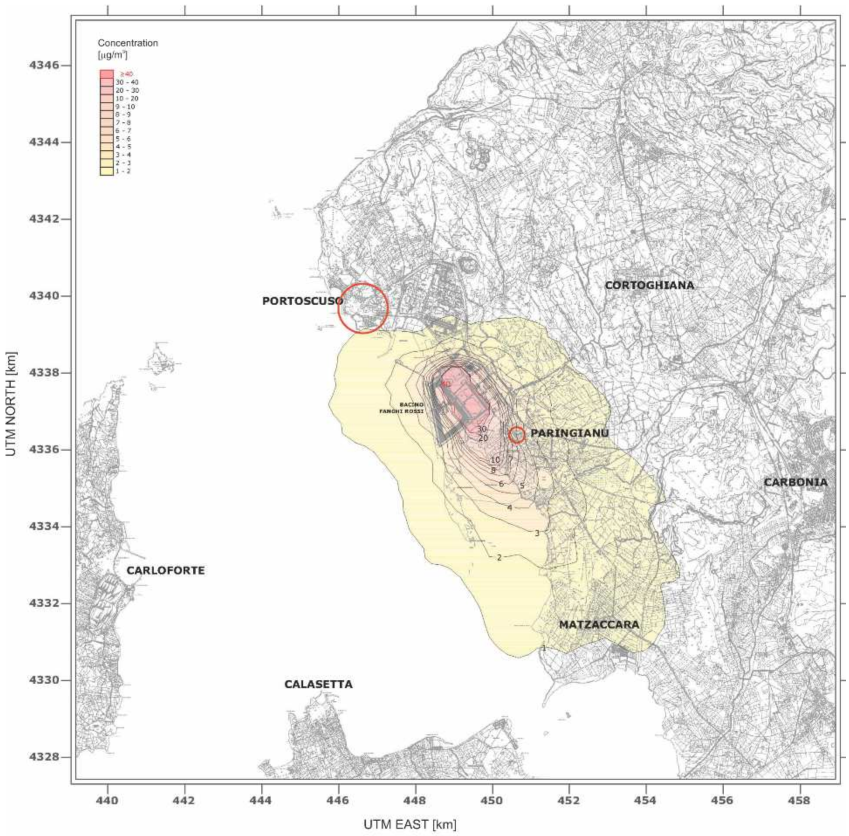

Figure 7. PM10 isoconcentration curves of the annual mean (scenario 1)

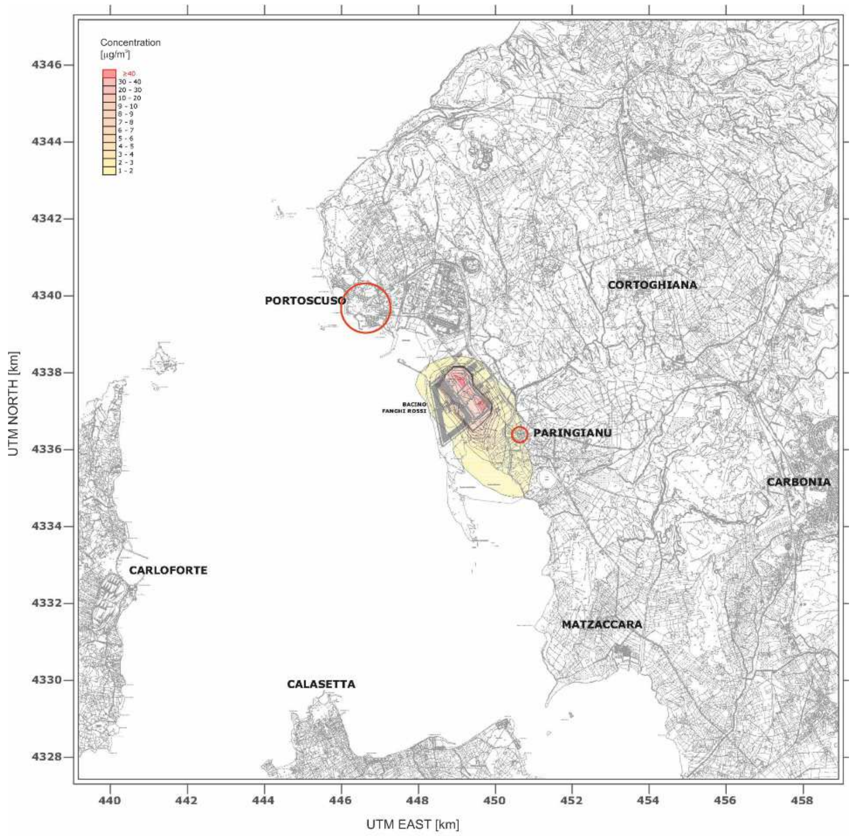

Figure 8. PM10 isoconcentration curves of the annual mean (scenario 2)

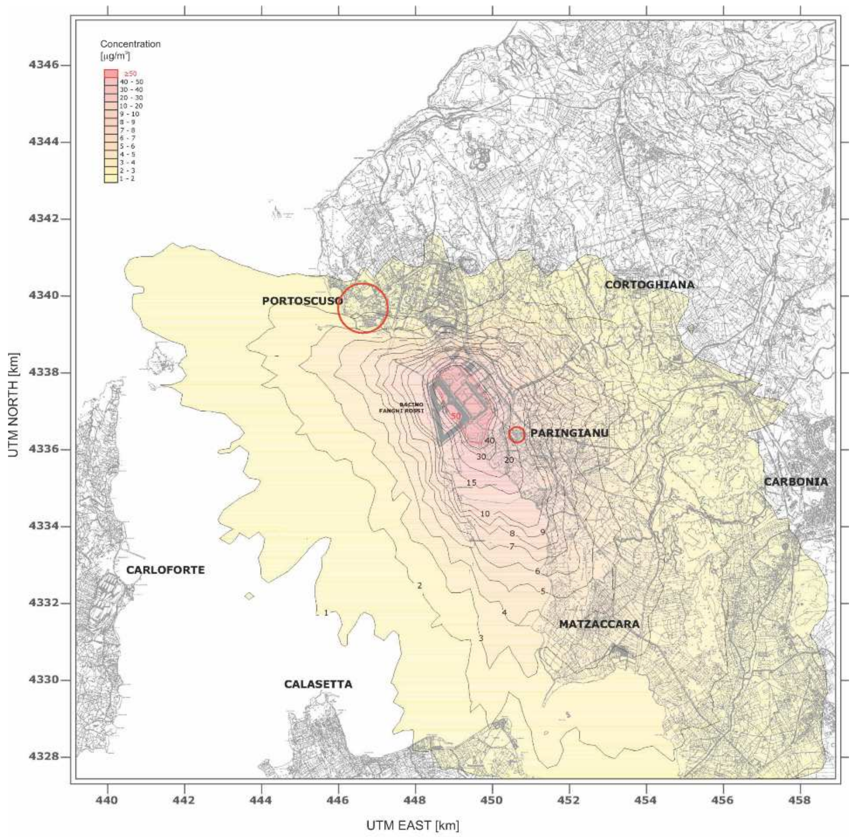

Figure 9. PM10 isoconcentration curves of the 90.4th percentile of the daily mean (scenario 1)

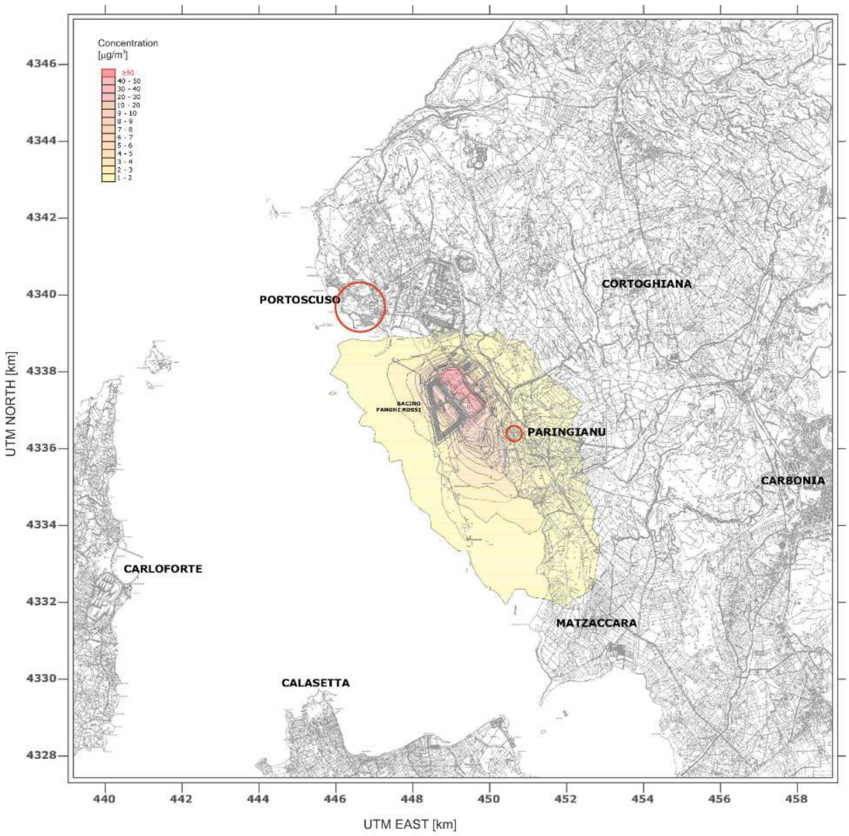

Figure 10. PM10 isoconcentration curves of the of the 90.4th percentile of the daily mean (scenario 2)

The maps highlight the correlation between the dispersion phenomenon and the frequency wind distribution. The comparison of the two scenarios demonstrates the effectiveness of the emission reduction measure (watering of unpaved travel surfaces and Sector D bottom barrier), in particular for the downwind receptors with respect to the dominant wind direction from North-West.

The PM10 concentration resulting from the CALPOST elaborations at the four monitoring stations (CENPS2, CENPS4, CENPS6 e CENPS7) are reported in Table 5, for scenario 1 and scenario 2.

As mentioned before, the resulting concentrations in CENPS6 and CENPS7 are representative of the air quality in Paringianu and Portoscuso respectively. The numerical results highlight an 80% reduction of airborne dust concentration in Paringianu, when considering the effect of unpaved travel surfaces and Sector D bottom barrier watering.

Table 5. Dust dispersion simulation results: PM10 concentration values at the four monitoring stations

		Highest daily mean [µg/m³]	**90.4th percentile of the daily mean [µg/m³]**	**Annual mean [µg/m³]**
Scenario 1	**CENPS2**	27.05	1.57	0.63
	CENPS4	12.20	1.19	0.34
	CENPS6	115.15	10.45	4.10
	CENPS7	31.67	1.71	0.55
Scenario 2	**CENPS2**	5.65	0.36	0.14
	CENPS4	2.74	0.26	0.08
	CENPS6	24.46	2.27	0.88
	CENPS7	6.64	0.37	0.13

4 The PM10 impact assessment results

In order to evaluate the global impact on air quality, the average values of the background concentrations measured by the monitoring stations from 2006 to 2013 (Table 2) were added to the simulated values at the corresponding points in the simulation domain. As regards the long-term period (a calendar year), for each of the four points (CENPS2, CENPS4, CENPS6 e CENPS7) the average value of the annual background concentrations (last column in Table 2) has been added to the concentration simulated with CALPUFF. The same operation has been carried out for the short-term period (one day), by adding the average value of the 90.4th percentile background concentrations (in this case, only for CENPS2, CENPS4 and CENPS6, as no background data was available for CENPS7) and the corresponding simulated value.

As mentioned above, the Directive establishes the limit values of PM10 concentration, for one day (50 µg/m^3, not to be exceeded more than 35 times a calendar year) and for a calendar year (40 µg/m^3). The PM10 impact results reported in Table 6 show that both the exposure limits established by law are not exceeded. The highest concentrations were estimated at the station CENPS2: the result is correlated to the high values of the background air quality.

Table 6. PM10 impact results

		90,4th percentile of the daily mean [µg/m^3]	**Annual mean [µg/m^3]**
		Short-term limit value 50 µg/m^3	*Long-term limit value 40 µg/m^3*
Scenario 1	**CENPS2**	45.70	30.03
	CENPS4	33.03	23.15
	CENPS6	28.33	28.96
	CENPS7	n.d.	28.06
Scenario 2	**CENPS2**	45.48	29.09
	CENPS4	32.85	22.30
	CENPS6	26.94	22.61
	CENPS7	n.d.	26.90

5 Conclusions

The article deals with the emission of fugitive dust from a major red mud basin located in the south-west of Sardinia, where the prospect of a change in the storage practices from lagooning to dry disposal is likely to cause the increase of PM pollution in the surrounding area.

In accordance with the procedures established by the Directive 2011/92 (EIA Directive - *Environmental Impact Assessment*), the environmental impact has been evaluated on the basis of the *ante operam* condition of the air quality provided by the public monitoring network installed by RAS (Regione Autonoma della Sardegna) in the Sulcis-Iglesiente sub-region.

The additional contribution of the red mud basin, in the hypothesis of dry disposal, has been calculated by implementing the CALPUFF modelling code suggested by US EPA. The emission data used in the simulations includes all the elementary activities contemplated in the conversion project, divided into two main stages: the construction stage (to adapt the plant and the existing basin) and the landfill operation stage (to dispose the dried residue). For all the elementary activities with a potential for emitting fugitive dust, the emission factors have been calculated according to the appropriate algorithms suggested by US EPA and used as input data in the CALPUFF modelling code.

The simulation results highlight the correlation between the dispersion phenomenon and the frequency wind distribution. The effectiveness of the emission reduction control measure (watering of unpaved travel surfaces and new sector bottom barrier) has been investigated both for the short (one day) and the long-term period (one year).
The expected whole concentrations of the airborne dust, which accounts both for the pre-existing sources and for the BR basin, have been compared with the limit values established by the Directive 2008/50/EC on *Ambient air quality and cleaner air for Europe*: the PM10 impact assessment results show that both the exposure limits established by law are not exceeded.

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