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Multi-criteria analysis for site selection for the reuse of reclaimed water and biosolids

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ABSTRACT

Low pH soils with insufficient organic matter can benefit from the application of reclaimed water (RW) and biosolids. The presence of nutrients also aids plant growth. This paper presents the results of two integrated research studies, both carried out in the Beira Interior Region (Covilhã, Portugal); one used RW for irrigation, the other applied paper mill sludge to agricultural land. In both cases, multiple criteria based on GIS tools were used for site selection. In the first study, the characteristics of RW analyzed over 2 years were found suitable for crop irrigation. The RW had moderate organic content, low electrical conductivity (CE), high nutrient content (N, P), and low concentrations of nitrate, metals and phytotoxic elements (Al, B, Cl and Na). The multi-criteria analysis was carried out taking into account environmental, technical and economic criteria and a suitable area of 30.5 ha was found for RW irrigation. In the second work, the paper mill sludge was considered suitable for application to agricultural land. Its concentrations of N, P and heavy metals did not a present risk for soil contamination and were suitable for soil improvement and crop production. A multi-criteria analysis based on similar criteria was conducted and a suitable area of 253 ha was found for sludge application.

Keywords: reutilization, spatial analysis, topographic location.

Análise multicritério para a seleção de locais para o reuso de águas residuais tratadas e biosólidos

RESUMO

Os solos com baixo teor em matéria orgânica e com baixo pH podem se beneficiar da aplicação da água residual tratada e de biosólidos. A presença de nutrientes é também útil para o crescimento de plantas. Este artigo apresenta os resultados de dois trabalhos de pesquisa, ambos realizados na região da Beira Interior (Covilhã, Portugal), um com água residuária tratada (RW) utilizada para irrigação agrícola, o outro com lodo resultante do tratamento de efluentes da pasta de papel para aplicação em solo agrícolas. Em ambos os casos, uma análise multicritério com utilização de SIG foi utilizada para localização de sítios mais adequados para a sua aplicação. No primeiro trabalho, as características de uma RW analisada durante 2 anos foram consideradas adequadas para a irrigação de culturas, uma vez que apresentavam teores de matéria orgânica moderada, baixa condutividade elétrica (CE), alto teor de nutrientes (N e P) e baixas concentrações de nitrato, metais e elementos fitotóxicos (Al, B, Cl e Na). A análise multicritério foi realizada levando-se em consideração critérios ambientais, técnicos e econômicos, e resultou na seleção de uma área de 30,5 ha para irrigação. No segundo trabalho, o lodo foi considerado adequado para aplicação em solo agrícola, uma vez que seu teor de N, P e metais pesados não apresentavam risco de contaminação do solo e foram adequados para a melhoria da sua qualidade e da produção agrícola. A análise multicritério com base em critérios semelhantes permitiu selecionar uma área de 253 ha para a aplicação do lodo.

Palavras-chave: Análise espacial, localização topográfica, reaproveitamento.

1. INTRODUCTION

In regions with large population growth, the demand for water for human, industrial and agricultural activities is expected to grow, and the imbalance between available water supply and demand is expected to increase, especially in regions with initial deficits of water. Due to growing water stress, it is necessary to look at efficient and alternative uses of water resources in order to narrow the gap between supply and demand. On the other hand, industrialization also requires wastewater treatment and the consequent production of sludge (biosolids), the treatment and disposal of which is costly for users. Therefore, the integrated reuse of treated wastewaters (reclaimed water) and biosolids seems an attractive option for agricultural activities. It allows for the control of the pollution potential of these residues and for their application to irrigation, aquifer recharge, land recovery, crop production and urban uses.

Both reclaimed water (RW) and biosolids include organic matter and nutrients that can be useful for soil conservation or crop production. The organic matter aids in the recovery of degraded or eroded soils, while the presence of nutrients makes the residue suitable as fertilizer (USEPA, 2012). Since they normally have a pH over 7, they can also be useful for the correction of pH in acid soils. However, they can also include harmful compounds (*e.g.* heavy metals, PCBs and PAHs), dissolved salts (*e.g.* Al, B, Cl and Na) that can cause soil salinity, and pathogens. Therefore, the quality of both residues should be properly controlled before being applied to agricultural lands, which may cause additional operational costs for users.

RW results from wastewater treatment and is subject to strict regulations prior to discharge into streams or soils. The residuals present in RW (namely organic matter, N, P and other micronutrients) may be useful for soil correction and crop irrigation. However, the presence of pathogens may require a polishing treatment as observed in Marecos do Monte and Albuquerque (2010a, b). The use of RW for irrigation is recognized internationally as a practice for integrated water resource management (Asano et al., 2007; Locussol et al., 2009; UNESCO, 2012; Jimenez et al., 2010). Brazilian and European legislation (EP, 1991; Brasil, 2005) has pointed out the need for increasing the use of RW in agricultural activities.

Paper mill sludge compost (PMSC) is produced during the treatment of wastewater from the paper industry. In the last decades, PMSC has been mainly burned or disposed of at landfills (Glenn, 1998). PMSC is high in cellulose and has suitable organic matter and nutrients (*e.g.* Ca, K, N, Na and P) for poor soil recovery and crop production (Foley and Cooperband, 2002; Jordan and Rodriguez, 2004; Camberato et al., 2006). The content of toxic elements is considered low (Phillips et al., 1997) and its organic matter, carbonate and silicate can even reduce harmful mobile metals in soils since they can be adsorbed into the soil particle surface (Battaglia et al., 2007). Current waste management strategies developed by international institutions such as the World Bank, the United Nations and the European Union point out the need of increasing the reuse of sludge (EP, 2008; EC, 2012; Hoornweg and Bhada-Tata, 2012). This practice, besides improving soil fertility and waste reuse, also reduces treatment and disposal costs. Brazilian and European legislation classifies the biosolids as solid waste that is not inert (EC, 2000; ABNT, 2004), suggesting that such wastes should be reused or valorised rather than disposed of (Brasil, 2010; EC, 2012). In Brazil, there are studies of WWTP irrigation agriculture in different cultures. Dantas et al. (2014), using WWTP of the city of São Cristóvão-SE to irrigate radishes, found that the resulting radishes were within the standards established by law. Deon et al. (2010) and Freitas et al. (2013) showed gains in productivity of cane sugar with drip irrigation of effluent. Varallo et al. (2010), working with red-yellow latosol reported that the use of reclaimed water for agronomic purposes should be applied in a rational manner, especially by monitoring the elevation of sodium.

Therefore, the integrated reuse of RW and PMSC in soils can increase its organic matter and nutrient content, improve soil's physical properties (*e.g.* lower bulk density, greater soil aggregation and water holding capacity), and increase its pH (Camberato et al., 2006; Asano et al., 2007), and may therefore be viewed as suitable soil amendments and plant nutrient sources.

Due to the large amount of complex information that must be accessed, integrated and analyzed (*e.g.* characteristics of the RW and biosolids, soil characteristics, type of crop production, water demand and nutrients for crop production, land use, environmental and legal restrictions, accessibility) geographical information systems (GIS) multicriteria analysis can be useful for data georeferencing, manipulation, conversion, analysis and map construction (Gemitzia et al., 2007; Kallali et al., 2007).

This paper presents the results of the application of GIS-based multicriteria for site selection of suitable areas for the application of RW and biosolids for agriculture.

2. MATERIAL AND METHODS

2.1. Characterization of the reclaimed water and the area for irrigation

The first study was conducted in a peri-urban region of Covilhã (Portugal) near an agricultural area with small, but with well-defined agricultural parcels (40° 15' 00'' N, 72° 29' 00'' W). The RW produced at the local wastewater treatment plant (an infrastructure sized for the equivalent of 4000 inhabitants, consisting of bar racks, grit chambers, a primary settling tank and biological aerated filters) was monitored between January and December of 2007 including the daily flow-rate measurement and the collection of bi-monthly samples (22 samples in total) of the raw influent and the RW. The samples were analyzed to evaluate the following parameters: pH, temperature, electrical conductivity (EC), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), ammonia (NH_4), nitrite (NO_2), nitrate (NO_3), total phosphorus (TP), sodium (Na), magnesium (Mg), calcium (Ca), potassium (K), chloride (Cl), boron (B), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn), total coliforms (TC), faecal coliforms (FC), *E. coli* and helminth eggs (HE). All of the analyses were conducted using the standard methods presented in APHA et al. (1999).

An area of 410 ha of agricultural parcels were demarcated near the village of Boidobra (Covilhã, Portugal) as shown in Figure 1, using extracts of Military Map No. 235

(1/25,000 scale), altimetry data (1/25,000 scale) and orthophotomaps (photogrammetric flight of 2004, 1/5,000 scale) and other local georeferenced elements (*e.g.* location of the WWTP and the agricultural parcels).

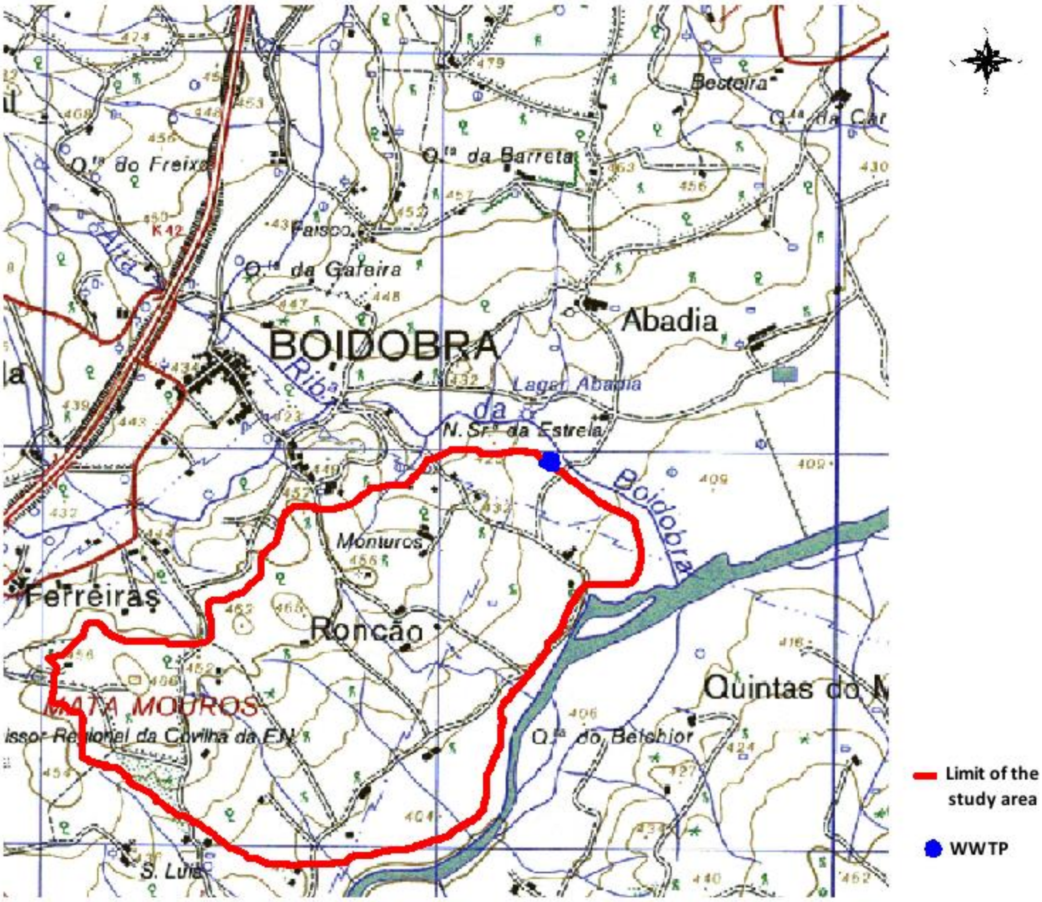

Figure 1. Selected area for reclaimed water irrigation in Covilhã, Portugal (40° 15' 00'' N, 72° 29' 00'' W).

The selection of the agricultural parcels for irrigation was based on environmental, technical and economic criteria according to the suggestions of Asano et al. (2007), Marecos do Monte and Albuquerque (2010b) and USEPA (2012) as follows:

a) Environmental criteria
- Land use (the Corine Land Cover map was used to evaluate the potential land use of the studied area);
- A safety distance of 50 m from natural water resources, 100 m from water supply sources and water reservoirs used for human consumption; and 200 m from urban residential areas.

b) Technical criteria
- Annually available RW volume and its physical, chemical and microbiological characteristics;
- Water demand for crop production in the agricultural parcels;
- Nutrient demand for crop production;
- Tolerance of crops to toxicity and salinity;
- Slopes (irrigation should be preferably applied to areas with slope up to 12%, since higher slope increases runoff, soil erosion and thus soil instability, which risks basin safety and increases refilling costs);

- Groundwater table (aquifers should be sufficiently deep and transmissive to prevent excessive rises of the groundwater table due to infiltration; the minimum static level was setup in 5 m in order to prevent groundwater contamination).

c) Economic criteria

- A maximum distance of 4 km from the RW production point was defined as economically viable for reuse (this criterion included water transfer costs from the WWTP to the agricultural parcels).

2.2. Characterization of the paper mill sludge and the area for application

The second work was developed in a larger agricultural area close to the first study (40° 15' 00" N, 72° 29' 00" W) and within an area covered by an irrigation plan, using paper mill sludge produced at a paper industry WWTP (Figure 2), which produces around 17 ton day^{-1} of sludge. The data were collected from a sludge characterization report supplied by the industry, which included information on the following parameters: pH, organic matter content, TN, NH_4-N, TP, Cd, Cr, Cu, Ni, Pb and Zn. All the analyses were conducted using standard methods presented in APHA et al. (1999).

Figure 2. Sample of pulp mill sludge.

An agricultural area of 1600 ha was selected in the peri-urban area of Covilhã (Portugal) for potential sludge application as shown in Figure 3, using extracts of Military Map No. 235 and 236 (1/25,000 scale), altimetry data (1/25,000 scale), ecological protected areas and agricultural protected areas (1/25,000 scale), a map of the Perimeter Irrigation Block of Covilhã-Fundão (1/25000, scale) orthophotomaps (photogrammetric flight of 2004, 1/5,000 scale) and other local georeferenced elements (*e.g.* location of the industry and the agricultural parcels).

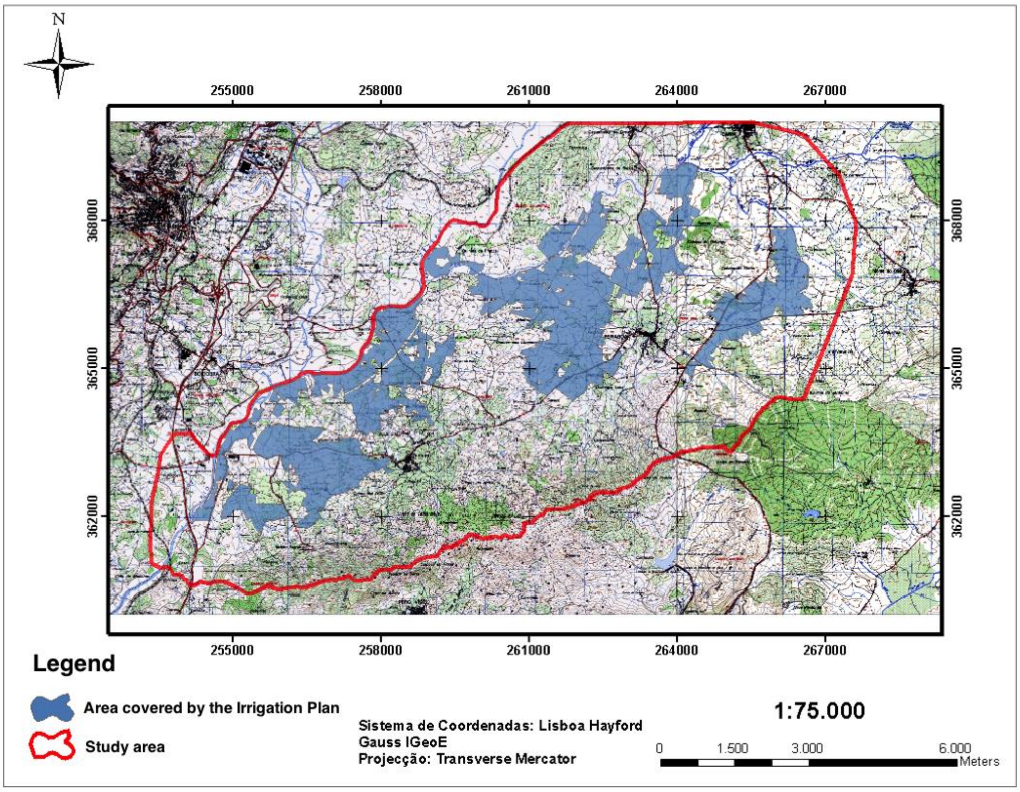

Figure 3. Selected area for sludge application in Covilhã, Portugal (40° 15' 00'' N, 72° 29' 00'' W).

The selection of the agricultural parcels for irrigation was based on environmental, technical and economic criteria according to the suggestions of MADRP (Portugal, 1997), USEPA (1997), ESD (Alberta, 1999) and DELG (Ireland, 2008), as follows:

a) Environmental criteria

- Areas with deep soils and classified as classes A and B according to the World Reference Base for soil resources (Deckers et al., 1998);
- A safety distance of 50 m from natural water resources, 100 m from water supply sources and water reservoirs used for human consumption, 200 m from urban residential areas, 30 m from borders of navigable waters and 10 m away from borders of non-navigable waters;
- Land uses (the Corine Land Cover map was used to evaluate the potential land use of the studied area). Areas for biological agriculture were skipped since sludge application is not allowed in soils with such activity.

b) Technical criteria

- Dry sludge application rate of 6 ton ha^{-1} $year^{-1}$;
- Annually available sludge volume and its physical and chemical characteristics;
- Nutrient demand for crop production;
- Tolerance of crops to toxicity and salinity;
- Slopes (sludge application should be preferably applied in agricultural parcels with slopes up to 12%);
- Groundwater table lower than 5 m.

c) Economic criteria

- A maximum distance of 8 km from the sludge production point was defined as economically viable for reuse (this criterion included sludge drying and transfer costs from the Celtejo industry to the agricultural parcels).

For each work (application of RW or biosolids), a spatial analysis was conducted over thematic layers (*thematic map*). The thematic layers were developed from geographical data obtained from official sources, georeferenced data and data generated using satellite images and orthophotos. Each point (cells representing 10 m × 10 m) in each layer took a value (0 or 1) according to exclusion and inclusion criteria. Map algebra was used to make a boolean operation between grid cells of different thematic maps in order to generate a final map with the agricultural parcels for the application of RW. All the operations were conducted using the software ArcGIS 9.1 (ESRI, USA) and the ArcCatalog and ArcMap applications.

All the physical, chemical and microbiological parameters were determined according to standard methods (APHA et al., 1999).

In both studies, taking into account the environmental, technical and economic criteria, the exclusion areas were coded as 0 and the inclusion areas as 1. A GIS in raster format was used to create a map with the location of the agricultural parcels and the results were processed according to the algebra of maps (maps overlapping for the different variables, operated in 10 m × 10 m sized cells).

3. RESULTS AND DISCUSSION

3.1. Site location for reclaimed water reuse

The characteristics of the RW are presented in the Table 1. The annual net volume of RW produced at the WWTP is approximately 170,000 m^3, based on the average flow-rate.

Table 1. Reclaimed water characteristics

Parameter	Value	Parameter	Value
Flow rate (m^3 d^{-1})	461	K (mg L^{-1})	56.7
Temperature (ºC)	16.4 - 2.5	Na (mg L^{-1})	102.2
pH	6.6 - 7.5	Mg (mg L^{-1})	12.2
EC (dS m^{-1})	0.38	As (mg L^{-1})	0.01
BOD_5 (mg L^{-1})	32.1	Cd (mg L^{-1})	0.02
DQO (mg L^{-1})	96.1	Cr (mg L^{-1})	0.15
TSS (mg L^{-1})	25.2	Co (mg L^{-1})	0.01
NH_4-N (mg L^{-1})	33.4	Hg (mg L^{-1})	0.01
NO_3-N (mg L^{-1})	3.4	Ni (mg L^{-1})	0.11
TN (mg L^{-1})	44.2	Pb (mg L^{-1})	0.08
TP (mg L^{-1})	8.2	Zn (mg L^{-1})	0.21
Al (mg L^{-1})	1.13	TC (NMP 100 mL^{-1})	$1.1x10^5$
B (mg L^{-1})	0.18	FC (NMP 100 mL^{-1})	2.1 $x10^4$
Ca (mg L^{-1})	44.2	*E. coli* (NMP 100 mL^{-1})	3.4 $x10^4$
Cl (mg L^{-1})	31.3	HE (eggs 10 L^{-1})	ND

Note: average values for 22 samples, ND: not detected.

The physicochemical characteristics of the RW suggest that it is suitable for crop irrigation, namely for the irrigation of fruit trees and vinery (Asano et al., 2007; Dantas et al., 2014). It has moderate organic content, high nutrient content (which is useful for crop production), low nitrate concentrations (it does not present a risk for groundwater contamination), low heavy metal concentrations, low EC (only values above 0.7 dS m^{-1} may be considered a risk for soil salinity) and is not phytotoxic for those crops (the concentration of Al, B, Cl and Na are below the recommended values for crop irrigation set up in USEPA (2012), Asano et al. (2007). However, the pathogenic content (TC, FC and *E. coli*) is not suitable for irrigation (WHO, 2006; Marecos do Monte e Albuquerque, 2010b; USEPA, 2012) and must be removed before the use of RW.

By overlapping all the criteria associated with each variable to the parcels with dominant crops (mainly fruit trees, corn, olive trees and vine) the agricultural parcels most suitable for irrigation were obtained as presented in Table 2 and Figure 4. A total suitable area of 30.5 ha was thereby found for irrigation, located within 1.8 km from the WWTP, which is the economical criterion allowed for the study.

Table 2. Areas for crop irrigation.

Type of crop	**Needs of water (m^3 ha^{-1} ano^{-1})**	**Volume of reclaimed water to be used (m^3 $ha^{-1}$$year^{-1}$)**	**Area for irrigation**	
			(ha)	**(%)**
Fruit trees	7500	85200	11.36	37.2
Corn	2500	11300	4.52	14.8
Olive trees	5300	46100	8.70	28.5
Vine	4600	27400	5.96	19.5
Total		**170000**	**30.53**	**100**

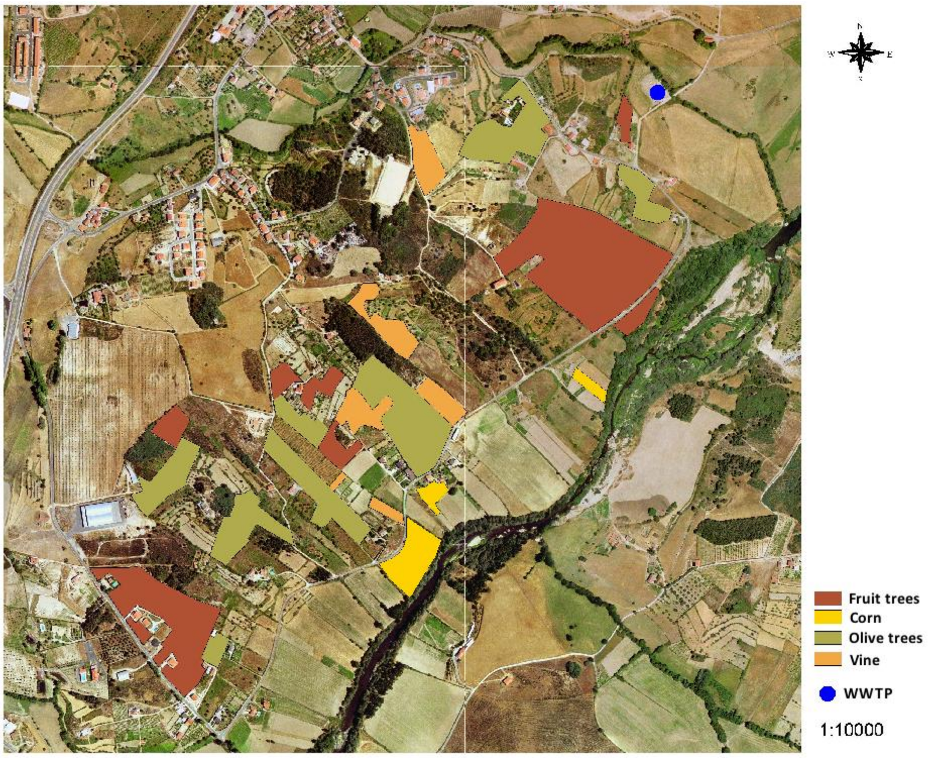

Figure 4. Agricultural parcels selected for irrigation with reclaimed water, Covilhã, Portugal (40° 15' 00" N, 72° 29' 00" W).

Taking into account the average concentrations of nutrients (N and P) and heavy metals, the yearly available volume of RW and the total area for crop irrigation, the yearly load of each compound to be added to the soil was computed. With respect to metals, the results show an higher load of 1.7 kg ha^{-1} $year^{-1}$ for Zn and values under 1 kg ha^{-1} $year^{-1}$ for other metals, which are all much lower than the limits defined by WHO (2006), Asano et al. (2007) and Marecos do Monte e Albuquerque (2010b).

Regarding the content of N and P, the maximum loads that would be added to the soil yearly would be 143 kg TN ha^{-1} $year^{-1}$ and 34 kg TP ha^{-1} $year^{-1}$, respectively, which are below the limits defined by several guides for good agricultural practices (USDA, 1994; Portugal, 1997; Ireland, 2008).

3.2. Site location for the resuse of biosolids

Primary sludge (produced at the primary settling tank) presents both higher organic matter and higher dry matter than secondary sludge (a biological sludge produced at the secondary settling tank), because it is less mineralized (Table 3). It also has a higher content of heavy metals, but less concentration of N and P as also observed by Camberato et al. (2006). However, the concentrations of heavy metals in both types of sludge are below the limits recommended by the same guides and high concentrations are not expected in soils after the incorporation of sludge. Both sludges present a good pH for land application since the limit stated in several manuals and codes of good practice is 5 (USEPA, 1997; Alberta, 1999; Portugal, 1997; Ireland, 2008).

Table 3. Pulp mill sludge characteristics.

Parameter	Primary sludge	Secondary sludge	Parameter	Primary sludge	Secondary sludge
Dry matter (DM, %)	25	10	Cd (mg kg^{-1})	1.4	0.34
Organic matter (OM, %)	47	11	Cu (mg kg^{-1})	13	2.8
pH	7.2	7.8	Cr (mg kg^{-1})	19	1.9
TN (mg kg^{-1})	38	2560	Ni (mg kg^{-1})	10.5	1.44
NH_4-N (mg kg^{-1})	4	1090	Pb (mg kg^{-1})	13.2	1.1
TP (mg kg^{-1})	167	370	Zn (mg kg^{-1})	83	12.9

Results also show that the amount of N to be introduced in the soils of the study area is much lower than the limits recommended by several guides (Portugal, 1997; Ireland, 2008) even for areas sensitive to nitrate leaching. Therefore, it seems reasonable to assume that sludge application rates higher than 6 ton ha^{-1} $year^{-1}$ can be applied if the amount of N in soil does not exceed 210 kg N ha^{-1} $year^{-1}$ and if both the quality of water sources and the risk of nitrate percolation in the soil were properly assessed.

The characteristics and types of crops can have different susceptibility to pulp mill sludge. Therefore, taking into account the restrictions set forth in Directive 86/278/EEC, agricultural parcels with the following crops were not considered: grassland or forage crops that are used for cattle feeding; vegetable crops and fruit crops with direct contact during the growing period; soils for vegetable or fruit cultures with direct contact for a period of 10 months before harvest.

A multi-criteria analysis was carried out over all the thematic maps and restrictions, resulting a suitable area of 253 ha for sludge application as shown in Figure 5 (green areas), which is enough for the application of all the sludge produced at the paper industry (approximately 6,386 ton $year^{-1}$), considering a rate of application of 6 ton ha^{-1} $year^{-1}$.

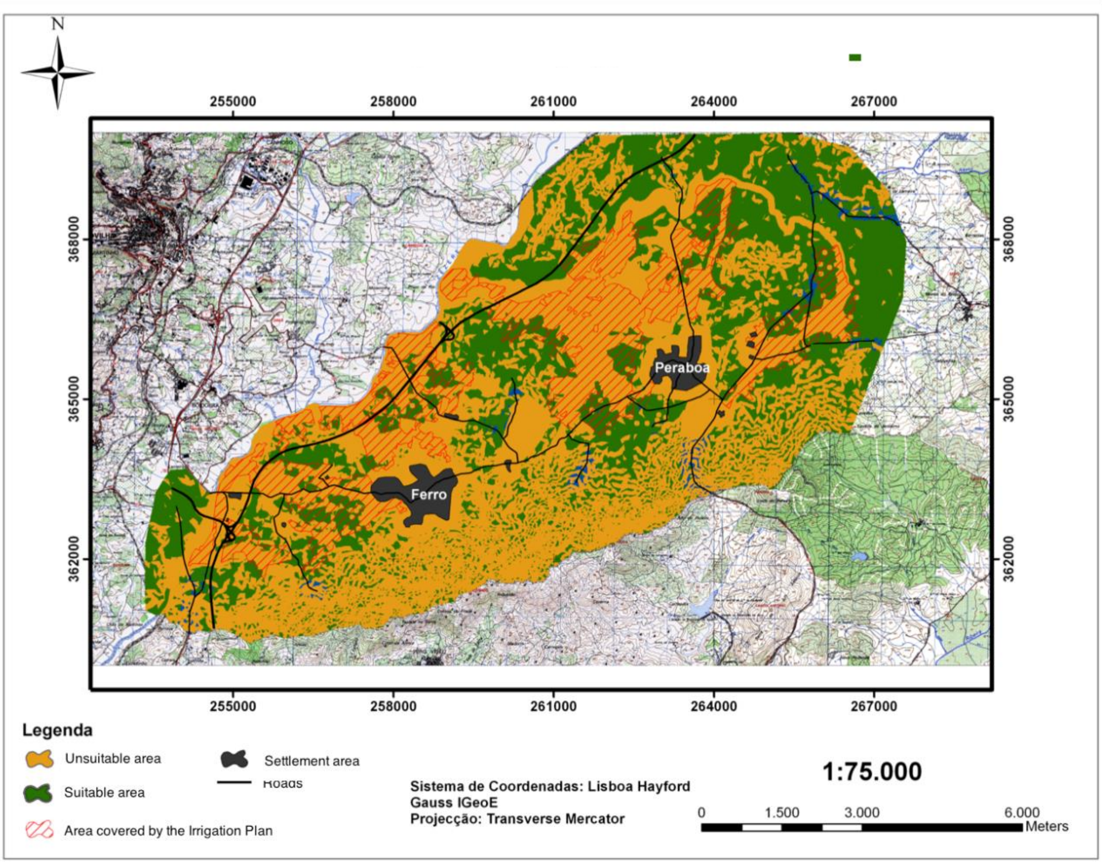

Figure 5. Suitable agricultural area for paper mill sludge application in Covilhã, Portugal (40° 15' 00" N, 72° 29' 00" W).

4. CONCLUSIONS

GIS multi-criteria analysis proved to be a very useful tool for selecting suitable agricultural parcels for the application of RW and biosolids. This tool allows georeferencing, storing, processing and manipulating complex information, as well as the use of map algebra operations over environmental, technical and economic criteria in order to create suitability maps. The use of reclaimed water represents an important water source for irrigation in peri-urban regions with water shortages, with important environmental and economic benefits. Pulp mill sludge is suitable for application to agricultural land either for organic correction of soils or as fertilizer for crops.

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