# SITE SELECTION FOR RECLAIMED WATER INFILTRATION USING GIS TOOLS

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## EXECUTIVE SUMMARY

In the Beira Interior region (Portugal) some sources of water do not present characteristics suitable for some uses due to pollution (namely associated to the discharge of point and nonpoint effluents) or are over-exploited (namely the aquifers). However, the water demand will grow in this region to meet socio-economic activities under development (*e.g.* the Cova da Beira irrigation plan, irrigation of golf courses and green areas and SPAs, as well as for distribution for human and industrial consumption), which will lead to the search of alternative sources of water. The region is characterized by many disperse urban agglomerates with less than 2,000 inhabitants, where the wastewater treatment plants (WWTP) are mainly ecological systems such as constructed wetlands (CW). In this context, the treated wastewater (reclaimed water) from these ecological treatment systems should be seen as a source of water to be used and not a waste to be eliminated.

After a monitoring campaign of two years at the CW system of Vila Fernando (Guarda, Portugal), the characteristics of the final effluent suggest that it could be used for aquifer recharge, not only because it is an area that uses many groundwater resources, but because other uses seem to be not relevant and would require a polishing treatment for the effluent, which would increase the costs of both investment and operation.

From 6 thematic maps and environmental, technical and economic criteria, it was selected a study area of 6687 ha. This area was analysed based on the manipulation of complex information using Geographic Information Systems (GIS), which consisted on overlapping areas of exclusion and inclusion from each thematic map and the use of algebraic operations (multi-criteria analysis) to obtain a final Suitable Map that indicated an area of 6.4 ha located in anthrosols as the most favorable ones for the infiltration of reclaimed water.

**KEY WORDS:** Aquifer recharge, GIS, infiltration, multi-criteria analysis, reclaimed water, reuse

# 1 INTRODUCTION

## 1.1 Background

The water shortage is increasing worldwide due to climate changes, recurrent droughts, over-exploitation of water resources, water quality degradation and the increase of water demand for human and industrial uses, with serious environmental, social and economic consequences. Water is not an unlimited resource, and its conservation is one of the most important pillars of sustainable development. Climate change has been influenced the variability of the hydrological regime in many parts of the world, which has also been affected the use of conventional sources of water for several applications. The increase of anthropogenic uses and the degradation of the water quality have lead to the search of alternative source as treated wastewater reuse (reclaimed water), which is very useful in areas with hydric deficit as the Beira Interior region in Portugal (Marecos do Monte and Albuquerque, 2010b; Pedrero *et al*., 2011; Silva, 2011).

The water demand in the region of Beira Interior is expected to increase due to the expected increase in agricultural activities associated to the local Irrigation Plan, as well as to touristic activities (SPA and golf courts). The region's aquifers might be over-exploited to satisfy these demands. One way that helps keeping soil water reserves is aquifer recharging with reclaimed water (Bower, 2002), which can be done by injection of water into the aquifer (injection in either the vadose zone or directly into the groundwater) or using surface infiltration basins (Asano *et al*., 2007). When the recharge involves soil infiltration, the soil will acts as a natural polishing treatment (also knowing as Soil Aquifer treatment (SAT)). The SAT reduces residual pollutant loads (organics, solids and nutrients), as well as the pathogen load of the reclaimed water since it allows filtration, adsorption and biodegradation removal pathways. The indirect recharge through infiltration basins is an interesting method for small or intermittent volumes came from small treatment systems as concluded by Pedrero (2010).

In the Beira Interior region there are hundreds of small wastewater treatment plants (WWTP), most of them constructed wetlands (CW), serving less than 2,000 inhabitants and the reclaimed water has been described as properly for reuse (Marecos do Monte and Albuquerque, 2010b; Pedrero *et al*., 2011; Silva, 2011). The opportunities for reuse in the south and northwest of the region are mainly for irrigation (agriculture, landscape and golf courts), industrial and humans activities. In the northeast region there are no many opportunities for irrigation and the aquifer recharge emerges as a good option.

The definition of a methodology for reclaimed water infiltration requires the collection, processing and analysis of complex information (*e.g*. land use data, soil and aquifer characteristics, environmental and legal restrictions, characteristics of the reclaimed water, accessibility and location and characteristics of the natural water resources), and the search of suitable sites for infiltration, which can be found using geographical information system (GIS) coupled with multi-criteria analysis. The use of GIS allows the georeferentiation, organization, processing and analysis of complex information, enabling the creation of exclusion and potential areas as already observed in other site location studies for evaluating groundwater pollution vulnerability to nitrate pollution (Lake *et al*., 2003), creation of a suitability map for pulp mill sludge application (Ribeiro *et al*., 2010), and location of wastewater treatment plants (Gemitzia *et al*., 2007).

## 1.2 Research objectives

This work aims to identifying potential sites for reclaimed water infiltration produced in a CW system located in a area with water shortage in the northeast of the Beira Interior region (Vila Fernando, Guarda, Portugal). The characteristic of the reclaimed water is analyzed and a GIS-based multi-criteria procedure is used for the location of infiltration basins.

# 2 MATERIALS AND METHODS

## 2.1 Study area

The first step involved the delimitation of the study area (**Figure 1**, red area) taking in account the location of the SPA of Cró, its protected area (**Figure 1**, blue area) and the point of reclaimed water production (the WWTP of Vila Fernando, with two CW beds). The area is located in the Northwestern part of the Beira Interior region in the district of Guarda (**Figure 1**) with altitudes ranging from 710 m to 875 m (**Figure 2**) having been delimited jointing the digitalized Military Maps No. 192, 193, 194, 203, 204, 214, 215, 225 and 226 (1/25,000 scale). The total measured area was 6687 ha.

The climate is Continental, with an annual average precipitation of 780 mm, average evapotranspiration of 700 mm and is expected a water deficit during the period June to September. The average temperature is 10.7 ºC (Silva, 2011). The dominant soils in the study area are anthrosols (61.81%), followed by umbrissols (22.56%), regossols (13,94%) and cambissols (1.69%). The land use is divided in open forests, cuts and new plantings (30.61%), agriculture in natural and semi-natural spaces (28.17%), complex cultural systems (21.64%), natural herbaceous vegetation (8.24%), broadleaf forests (5.29%), permanent pasture (2.67%), temporary cultures of rainfed (1.87%) and bush (1.51%) (Silva, 2011).

The local WWTP has a secondary treatment with two parallel CW with subsurface horizontal flow with, each with 23 m x 18 m (length × width). The beds were filled with Filtralite MR 3-8 (a commercial LECA) and colonized with common reeds (*Phragmites australis*). The secondary effluent (reclaimed water) is presently discharged into the Noéme river. The start-up f the system occurred in 2007 and will be operated during the next 40 years.

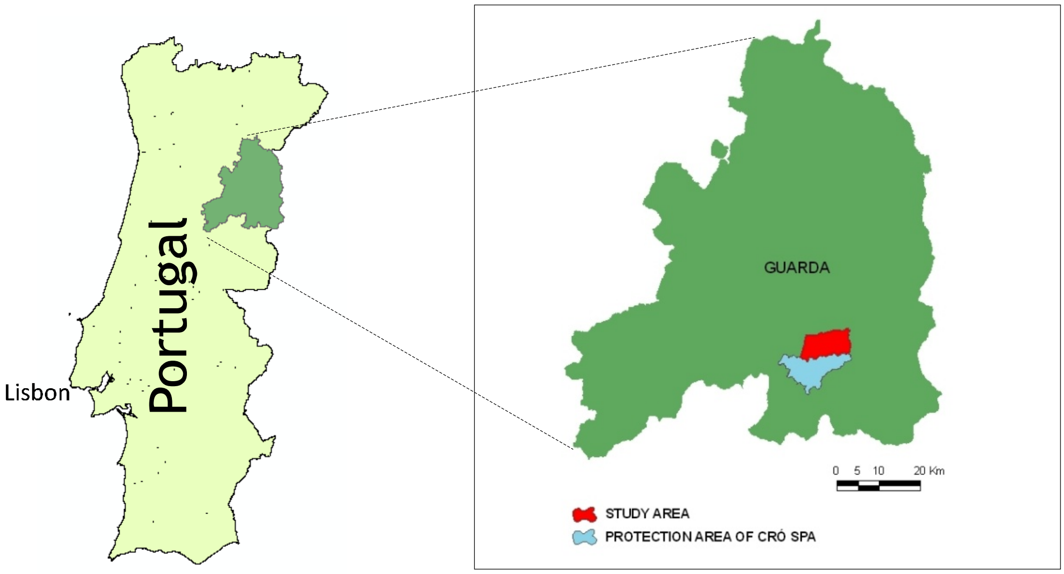



FIGURE 1 **Location of study area**

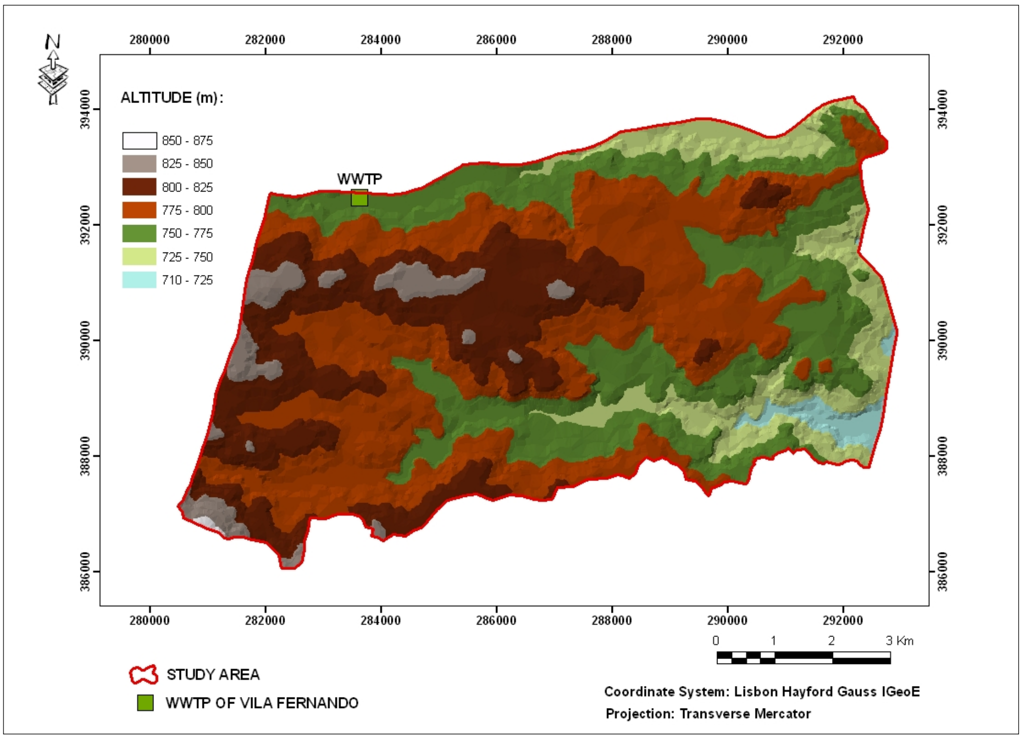



FIGURE 2 **Digital elevation model for the study area (cell size of 10 m × 10 m)**

## 2.2 Monitoring campaign at the CW beds

A monitoring campaign was set-up between November of 2007 and November of 2009, which included the daily measurement of flow rate and the collection of biweekly samples of the reclaimed water for determining the following parameters: pH, temperature, biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), ammonia nitrogen ($NH_4$-N), nitrate nitrogen ($NO_3$-N), total phosphorus (TP), electric conductivity (EC), sodium (Na), calcium (Ca), potassium (K), chloride (Cl), total coliforms (TC), fecal coliforms (FC), *Escherichia coli* (*E. coli*) and helminthes eggs (HE). In the last three samples it was also determined the magnesium (Mg), boron (B), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn).

## 2.3 Identification of areas for reclaimed water infiltration

This step included the identification of the areas suitable for reclaimed water infiltration taking into account environmental, technical and economic criteria (**Table 1**), as well as the protected area of the Cró SPA and the source of reclaimed water production (the WWTP of Vila Fernando). The restrictions presented in **Table 1** were selected according to the local conditions, legal restrictions (national and European legislation) and guidelines followed in other studies and documents (Angelakis *et al*., 2003; EPA, 2006; Bixio and Wintgens, 2006; Asano *et al.*, 2007; Marecos do Monte and Albuquerque, 2010a; Pedrero, 2010; Pedrero *et al*., 2011; Silva, 2011).

Using the available digitalized-based maps (military maps, ortophoto maps, Corine land cover map, type of soil map and digital elevation model (**Figure 2**)) it was produced 6 thematic maps for all environmental, technical and economic criteria. All the data were collected and treated in *vector* format or *raster* format, using the software *ArcGIS 9.2* (*ArcCatalog*, *ArcMap* and *ArcToolbox* applications). The digital elevation model (DEM) was built from altimetry data (elevation data) using a triangular irregular network (TIN).

Spatial analysis was carried out over all the variables, have been adopted a thematic layer (thematic map) for each variable. The thematic layers were developed from geographical data obtained from official sources, georeferenced data and data generated using satellite images and orthophotos. The maps are matrixes of cells, each cell representing 10 m × 10 m and taking the value 0 (restriction point – exclusion cell) or 1 (non-restriction point – inclusion cell) according to the exclusion and inclusion criteria presented in **Table 1**. Map algebra was used to make Boolean operations between grid cells of the different thematic maps in order to generate a final suitability map for the infiltration of reclaimed water.

TABLE 1 **Environmental, technical and economic criteria**

| Criteria | Restrictions |
|---|---|
| **Environmental** | To avoid contamination by infiltration of reclaimed water or contact with humans, the following restrictions were considered:<br>- A safety distance of 50 m away from water resources for irrigation;<br>- A safety distance of 100 m away from water supply sources for human consumption, including adduction pipes and reservoirs;<br>- A distance of 200 m way from urban residential areas. |
| **Technical** | - Annually available volume of reclaimed water;<br>- Land use (the Corine Land Cover map was used to evaluate the potential land use of the studied area; all the bush areas were considered since are uncultivated areas that can be used for infiltration);<br>- Slopes (infiltration should be preferably applied in agricultural parcels with slopes ranging between 0% and 12%, since higher slopes increase runoff, soil erosion and thus soil instability, which risks basin safety and increases refilling costs);<br>- Soil texture (vadose zones should not contain clay layers or other soils that could restrict the downward movement of water and form perched groundwater mounds; to avoid soil clogging and to assure the SAT, the soil must have less than 10% of clay fraction);<br>- Type of soil (the soil for reclaimed water infiltration should have the top section without soil rock; all soils were excluded except for Anthrosol, because they are soils with more than 1 m deep and have a texture such as fine sand that allows an infiltration rate of 1 m/d (most of the reclaimed water polishing occurs in the first 1 m of soil));<br>- Aquifer depth (aquifers should be sufficiently deep and transmissive to prevent excessive rises of the groundwater table due to infiltration. The minimum static groundwater level accepted for reclaimed water infiltration is 5 m in order to have a sufficient vadose zone for SAT). |
| **Economic** | Maximum distance of 8 Km: this criterion included water transfer costs from WWTP to the infiltration site, and the transport length should not exceed 8 Km. |

## 3 RESULTS AND DISCUSSION

### 3.1 Analysis of reclaimed water quality for aquifer recharge

The results of the 2 years monitoring campaign are presented in **Table 2**. Results showed that concentrations of TN, $NH_4$–N and TP are higher than the limits setup by national and European legislation for discharge in water bodies (Directive 271/91/EEC and Portuguese Decree-Law No. 236/98): maximum allowed values of 10 mg $L^{-1}$ ($NH_4$), 15 mg $L^{-1}$

(TN) and 3 mg $L^{-1}$ (TP). The FC load is not suitable for agricultural irrigation according to national legislation and international guides (Portuguese Decree-Law No. 236/98; Portuguese Standard NP 4434, 2005; Asano *et al*., 2007): maximum allowed values of 100 FC 100 $mL^{-1}$. The concentrations of heavy metals and nitrate are below the limits for both the discharge in water bodies and irrigation (Portuguese Decree-Law No. 236/98; EPA, 2004; Portuguese Standard NP 4434, 2005; Asano *et al*., 2007; UNESCO, 2009). To use this reclaimed water for agricultural, urban, industrial or landscape purposes it would be necessary a polishing treatment for reducing nitrogen, phosphorus and pathogenic loads as recommended in several studies (Asano *et al*., 2007, UNESCO, 2009; Marecos do Monte and Albuquerque, 2010a; Pedrero *et al*., 2011; Silva, 2011).

TABLE 2 **Characteristics of the wastewater in the WWTP of Vila Fernando**

| Parameters | Reclaimed water [1)] | Parameters | Reclaimed water [1)] |
|---|---|---|---|
| Flow rate ($m^3 d^{-1}$) | 58 ± 25 | K (mg $L^{-1}$) | 28.4 ± 5.3 |
| Temperature (ºC) | 15.3 – 3.9 | Cl (mg $L^{-1}$) | 79.5 ± 32.5 |
| pH | 6.3 – 7.7 | B (mg $L^{-1}$) | <0.02 |
| EC (dS $m^{-1}$) | 0.22 ± 0.02 | Cd (mg $L^{-1}$) | <0.02 |
| $BOD_5$ (mg $L^{-1}$) | 27.4 ± 7.2 | Cr (mg $L^{-1}$) | <0.1 |
| COD (mg $L^{-1}$) | 83.9 ± 13 | Cu (mg $L^{-1}$) | 0.01 ± 0.00 |
| TSS (mg $L^{-1}$) | 27.1 ± 18.3 | Ni (mg $L^{-1}$) | 0.05 ± 0.01 |
| $NH_4$-N (mg $L^{-1}$) | 54.4 ± 7.4 | Pb (mg $L^{-1}$) | <0.01 |
| $NO_3$-N (mg $L^{-1}$) | 0.8 ± 0.5 | Zn (mg $L^{-1}$) | < 0.01 |
| TN (mg $L^{-1}$) | 60.7 ± 13.8 | TC (NTU 100 $mL^{-1}$) | $1.95 \times 10^6$ ± 980 |
| TP (mg $L^{-1}$) | 6.9 ± 1.3 | FC (NTU 100 $mL^{-1}$) | $6{,}91 \times 10^5$ ± 652 |
| Na (mg $L^{-1}$) | 118.7 ± 11.4 | *E. Coli* (NTU 100 $mL^{-1}$) | $1{,}05 \times 10^4$ ± 540 |
| Mg (mg $L^{-1}$) | 0.21 | HE (eggs $10L^{-1}$) | 0 |
| Ca (mg $L^{-1}$) | 23.6 ± 3.1 | | |

[1)] Average and confidence interval calculated for a confidence level of 95% and the following number of samples: 40 (flow rate, temperature, pH, $BOD_5$, COD, TSS, $NH_4$-N, $NO_3$-N, TN, TP, Na, Ca, K and Cl), 10 (EC, Mg, B, Cd, Cr, Co, Ni, Pb , Zn, TC, FC, HE, *E.Coli*,).

When the infiltration is carried out on the soil surface or the unsaturated zone, much of the organic matter, forms of nitrogen and phosphorus, and heavy metals are removed or converted in the first meter of soil (Asano *et al*., 2007). The soil can act as filter with biological activity (SAT) as it occurs in the wastewater treatment processes through porous media (fixed-film processes). The biggest concern lies with nitrates, resulting from the oxidation of ammonia, which is very mobile in the porous media systems, as well as the bacterial load.

If the infiltration area is located in permeable sandy soils, with a distance from a winter water table superior to 5 m (minimum height of the unsaturated zone), the application of infiltration rates between 0.2 and 1 m $d^{-1}$ will reduce significantly the final concentration of organic matter, organic nitrogen, ammonia, nitrite, nitrate, TSS, heavy metals and pathogen load (Asano *et al*., 2007). Guessab *et al*. (1993) observed a removal of 3 to 4 logs of FC and *faecal streptococci* and a complete elimination of HE in 5 m of unsaturated zone in sandy soils, for an infiltration rate of 0.23 m $d_{-1}$. Brissaud *et al*. (1991) observed the removal of between 1.5 to 4 logs of FC in columns of fine sand (1 m depth) for infiltration rates between 0.5 and 1 m $d^{-1}$.

In the study area, the water depth of the aquifer ranges from 10 m to 50 m (Silva, 2011). Therefore, the most suitable site for the location of infiltration basins would be an area with sandy and thin soil, which would allow an infiltration rate of 1 m $d^{-1}$, or even higher, since the depth of the unsaturated zone is superior to 10 m. The infiltration area must be located away from the sulfurous aquifer protection area boundary, which feeds the SPA of Cró.

## 3.2 Location of potential areas for reclaimed water infiltration

The 6 thematic maps were produced according to the criteria of **Table 1** using spatial analysis as shown in the flowchart of **Figure 3**.

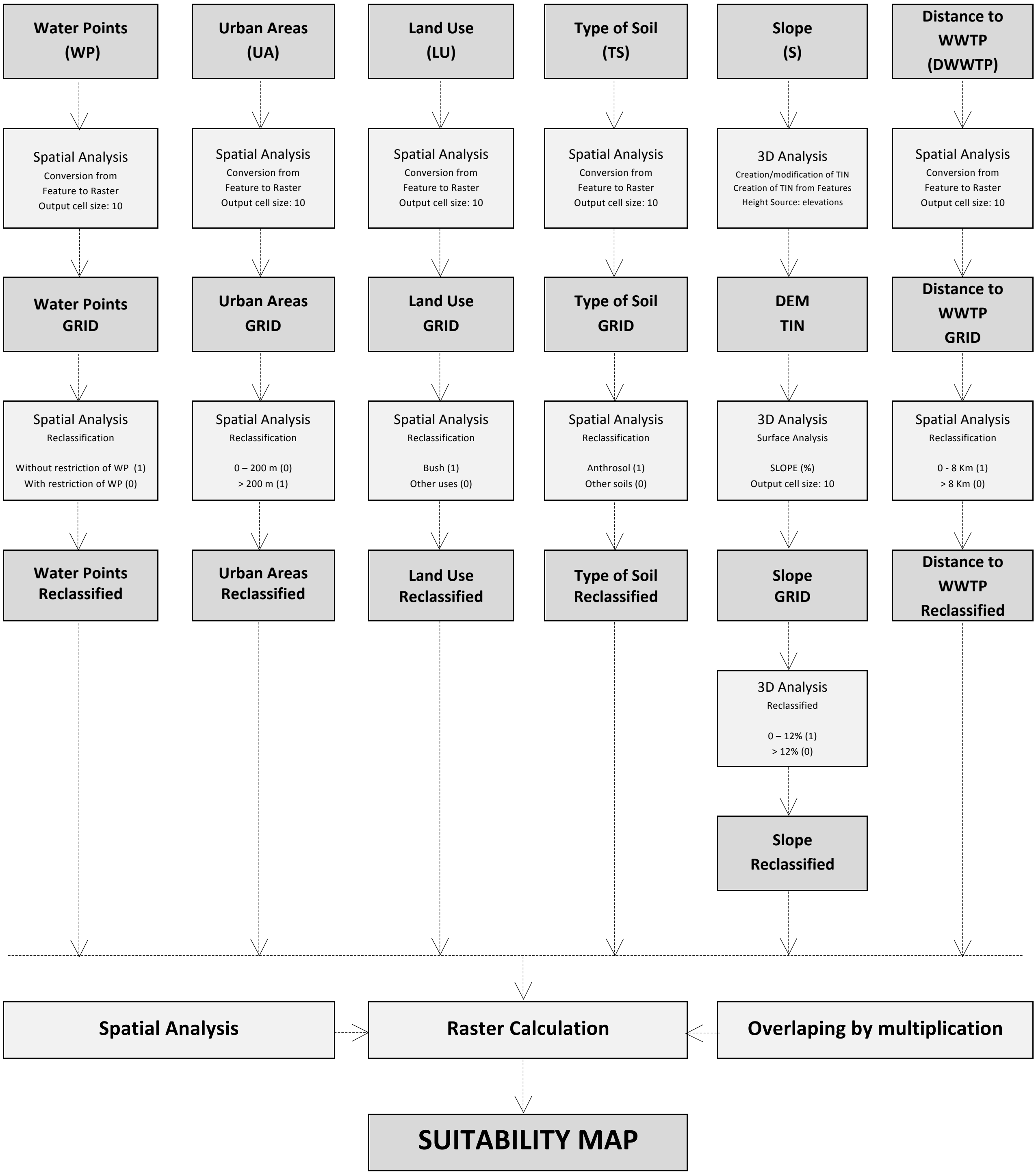



FIGURE 3 **Flowchart of spatial analysis operations for building the Suitability Map for reclaimed water infiltration**

Therefore, the elaboration of the suitability map involved a multi-criteria analysis using the method of Boolean overlaping, as suggested by Zhao *et al*. (2009) and Ribeiro *et al*. (2010), which consisted in the reclassification of the thematic maps in binary form (all the 10 x 10 m cells were coded as "0" or "1"), having been later combined according to logical operations of intersection and union of inclusion (any cell with a result of "1" was considered an area with suitability for infiltration) and exclusion (any cell with a result of "0" was considered an area without suitability for infiltration). The 6 thematic maps were classified as Water Points (WP), Urban Areas (UA), Land Use (LU), Type of Soil (TS), Slopes (S) and Distance from WWTP (DWWTP) and are presented in **Figure 4**.

The calculation procedure involved overlapping the exclusion and inclusion areas of each of the thematic maps on the study area, through algebraic operations of maps. The value of each cell of the Suitability Map resulted, therefore, from the sum of the multiplication of the weights assigned to each thematic map by the value stored in each of its cells (10 m x 10 m size) by means of algebraic maps.

The **Figure 5** shows the favorable areas and the areas with restriction for each variable. The more restrictive areas are the location of water resources (only 848.4 ha have no water resources) and the distance from the reclaimed water production point (approximately 5862.5 ha are located at less than 8 Km from the WWTP). Besides large areas with favorable slope (5863.9 ha), not urbanized (6091.3 ha) and occupied with anthrosol soils (4133.6 ha) were detected, both the uncultivated areas (100.4 ha) and the areas without water resources (848.4 ha) have conditioned the final area for infiltration. Therefore, only an area of 6.4 ha (0.1% of the total area of 6687 ha defined in **Figure 1**) fitted well the favorable criteria and it was considered for infiltration basins.

The final Suitability map was produced as presented in **Figure 6**. The area defined as favourable for reclaimed water infiltration is presented in blue. The use of GIS allowed georeference, storage, processing and manipulating complex information, where from 6 thematic maps and the definition of inclusion and exclusion zones, it was possible to produce a Suitability map with the location of areas for reclaimed water infiltration in an area of 6687 ha located in the region of Beira Interior.

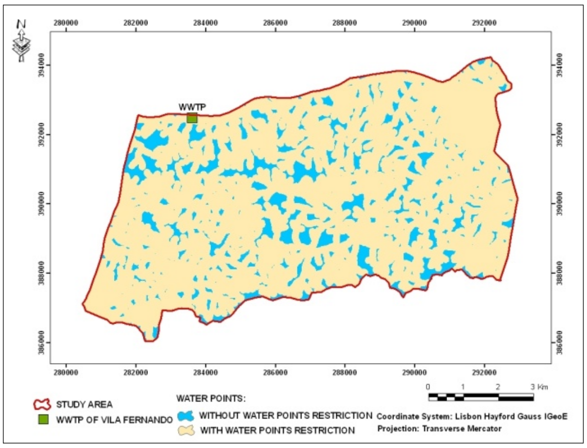
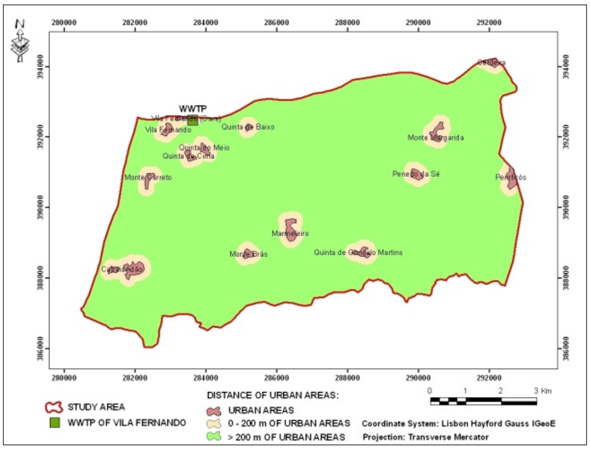
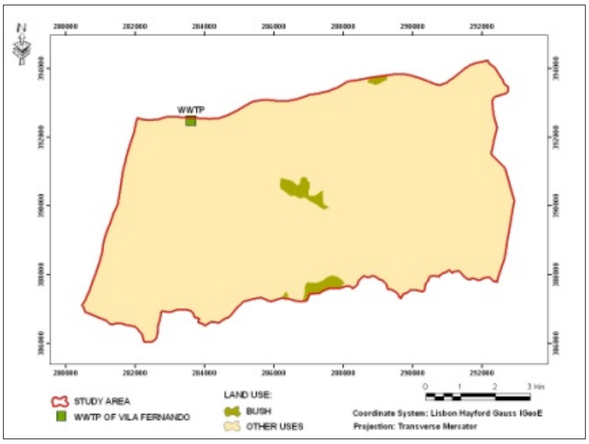
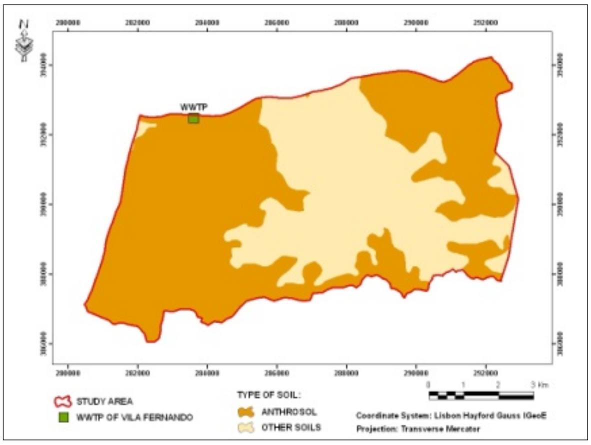
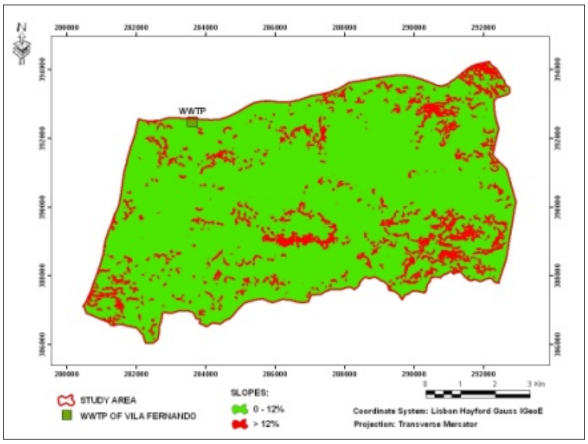
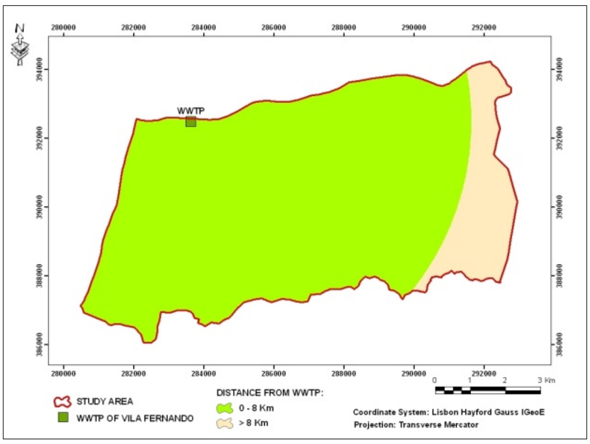
<table>
<tr><th>Water Points Thematic Map (reclassify)</th><th>Urban Areas Thematic Map (reclassify)</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Until 100 m of water lines and water tank (0)<br>Superior to 100 m of water lines and water tank (1)<br>Until 50 m of irrigation wells (0)<br>Superior to 50 m of irrigation wells (1)</td><td>Until 200 m of urban areas (0)<br>Superior to 200 m of urban areas (1)</td></tr>
<tr><th>Land Use Thematic Map (reclassify)</th><th>Type of Soil Thematic Map (reclassify)</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Bush (1)<br>Other uses (0)</td><td>Anthrosol (1)<br>Other soils (0)</td></tr>
<tr><th>Slope Thematic Map (reclassify)</th><th>Distance from WWTP Thematic Map (reclassify)</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Slopes between 0% and 12% (1)<br>Slopes superior to 12% (0)</td><td>Until 8 Km from WWTP (1)<br>Distance superior to 8 km from WWTP (0)</td></tr>
</table>

FIGURE 4 **Thematic maps**

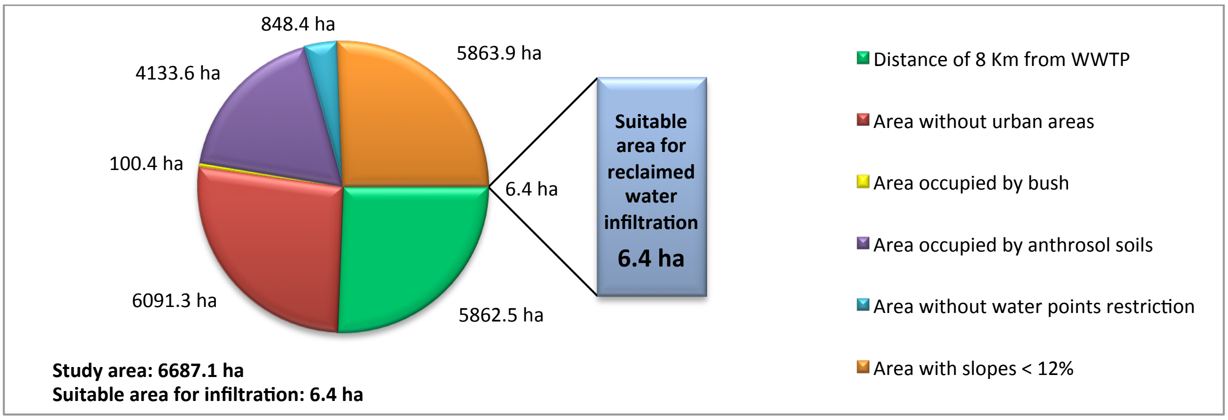



FIGURE 5 **Areas with restriction or favorable for reclaimed water infiltration**

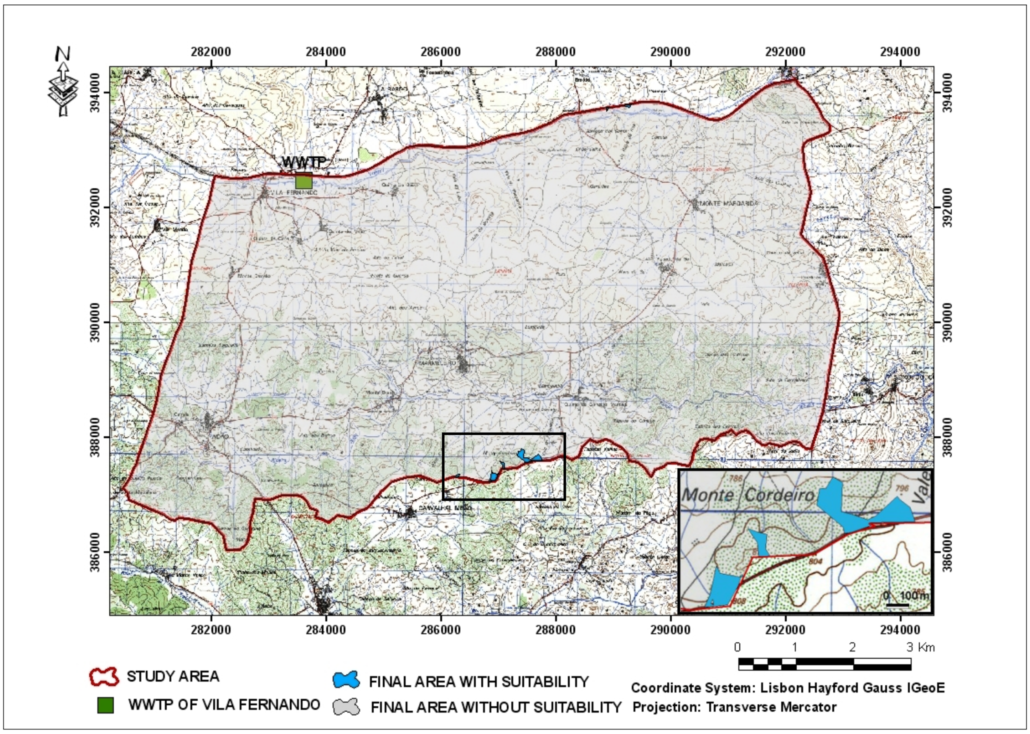



FIGURE 6 **Suitability map for reclaimed water infiltration**

## 4 CONCLUSIONS

The reclaimed water reuse for aquifer recharge can be a useful tool for the water conservation in regions with water shortage as the Beira Interior region, reducing also the discharge of treated wastewater into water streams. The data obtained in the two-years monitoring campaign at the WWTP of Vila Fernando shows that the characteristics of the reclaimed water are suitable for aquifer recharge. Although the loads of nitrogen, phosphorus and pathogens are high for most uses, it was found an area of 6.4 ha with suitable characteristics for infiltration. A GIS-based multi-criteria analysis was used for site location, which combined 6 thematic maps and environmental, technical and economic criteria.

## 5 ACKNOWLEDGEMENTS

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