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Optimization of the use of reclaimed water through groundwater recharge, using a Geographic Information System

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ABSTRACT

Integrated water resources management through the use of Geographic Information System tools, for optimization of the use of reclaimed water, was studied in the northwest of the Region of Murcia (Spain), a semi-arid region with scarce water resources—a limiting factor in socioeconomic development. In accordance with the principles of integrated water resources management, to promote the sustainable future supply and use, reclaimed water in the Region of Murcia is directly or indirectly reused, and this has contributed to a 13% increase in natural river basin resources. Technical, environmental, and economic criteria were selected in order to build ten thematic maps. Five wastewater treatment plants (WWTPs) were selected based on the technical and economic criteria of an annual volume treated of more than 500,000 m^3 (Bullas, Calasparra, Caravaca, Cehegín, and Moratalla). The data of the technical and environmental criteria are referred to the land area of the municipality, and the economic criteria data refer to an 8-km radius around each WWTP. The most restrictive variables were the soil texture and the availability of water supply sources, due to the presence of irregular terrain and water lines in the hydrographic basin of the studied area. After analyzing all the criteria established, of the total area studied (237,960 ha), only 2.7% (6,442 ha) is considered optimal for aquifer recharge. The application of multi-criteria analysis resulted in a final, optimal map showing areas appropriate for the infiltration of reclaimed water.

Keywords: GIS; Aquifer recharge; Reclaimed water use; Water scarcity

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1. Introduction

In Spain, the intensive agriculture is concentrated in the southeast, where fresh water is very scarce [1]. The present work was conducted in the Segura Basin (Murcia), located in southeast Spain with an area of 18,870 km^2 occupied by 1,944,690 inhabitants. The Murcia region is fully integrated in this basin, encompassing most of its surface area (59.3%) and population (73.3%). The Segura Basin has a semi-arid Mediterranean climate, with mild winters (11℃ on average in December and January) and hot summers (increases up to 45℃). The low annual rainfall (375 mm) contrasts with the high average potential evapotranspiration (ETo) (827 mm) [2].

The agriculture in this basin is among the most profitable in Spain. According to the Murcia Regional Ministry of Water and Agriculture, the annual volume of water necessary to cover the regional agricultural needs exceeds 880,000 ML [3]. Water reuse in Spain is currently estimated at about 368,000 ML [4], with around 100,000 ML (2012) being reused directly or indirectly in Murcia [5]. Approximately 50% of all wastewater treated has undergone additional tertiary treatment, as specified in Title 22 of the California Water Code [6]. Owing to the implementation of this practice, the supply of treated water has contributed to a 13% increase in natural river basin resources [7].

Soil secondary salinization in the semi-arid regions seriously affects the productivity of at least 20–30 million ha of agricultural land [8]. However, predominantly intensive agriculture may present a risk of soil salinization due to overuse of fertilizers or irrigation mismanagement. In the Region of Murcia, which accounts for most of the irrigated crops in the Segura basin, irrigated agriculture contributes 75% to the final agricultural production, with vegetables (38%) and fruits (21%) being the major contributors. In the Segura basin, the overexploitation of many aquifers has resulted in a widespread loss of water quality, especially in the lower areas of valleys and in the coastal zone. The continued use of these water resources for irrigation will probably put crops and the environment at risk from salinization, soil compaction, and undesirable ions toxicity [9]. An estimated 100,000 ha of land are irrigated with water from aquifers, of which 85% have very high level of salts [10].

Sustainable water resources management through the use of reclaimed water requires the design of integrated and adaptable systems, increasing efficiency of water use, and continuous efforts towards the protection of ecosystems [11]. With safeguards to protect groundwater quality, reclaimed water can be used for groundwater recharge. This application has many benefits, among which are the low cost of this tertiary treatment and the storage of good irrigation water quality for later use without loss by evaporation [12]. Spain has shown an increasing interest in aquifer recharge with reclaimed water because its use is included within Royal Decree 1620/2007, which regulates the reuse of treated wastewater. Although in the Region of Murcia, because of its setting, virtually all reclaimed water is used directly in agriculture; globally there is an increase in the use of reclaimed water for aquifer recharge. At present, the percentage of water reuse in the Region of Murcia is approximately 95%. The remaining 5% are effluents from some coastal wastewater treatment plants (WWTPs), for which saline intrusion makes the salinity levels too high for reuse in irrigation. Infiltration into the ground represents 1% of the total reclaimed water [13], although this percentage may increase during periods of the year with low water demand. Geographic Information Systems (GISs) allow the geo-referencing, organization, processing, and analysis of such complex information. They have been used in water resources management: in site selection for treated wastewater instream use [14], for artificial recharge [15], to assess water quality in drinking water [16] and reservoirs [17], and in site selection techniques for applications related to water reuse projects, such as aquifer recharge [9] and irrigation [18].

Groundwater recharge should be analyzed to assess the degree of environmental benefit—due to the increased aquifer levels when the water is reused directly—and the treatment cost, due to the reduction in treatment in the WWTP. Therefore, the main objective of this work was to identify optimal areas for groundwater recharge with reclaimed water in the northwest of the Region of Murcia, using GIS-based multi-criteria analysis, validating and demonstrating an innovative management system for the optimization of the reclaimed water from the technical, environmental, and economic points of view.

2. Materials and methods

2.1. Characterization of the study area

This step included the selection of a study area and the source of reclaimed water. The study area is located in the northwest part of the Region of Murcia, Spain (Fig. 1), with altitudes ranging from 218 to 845 m. It is influenced by a moderate Mediterranean climate, with an average annual precipitation of 367 mm, annual average temperature of 12.6℃, and average annual ETo of around 1,000 mm [19]. This low rainfall is unevenly distributed in time and space

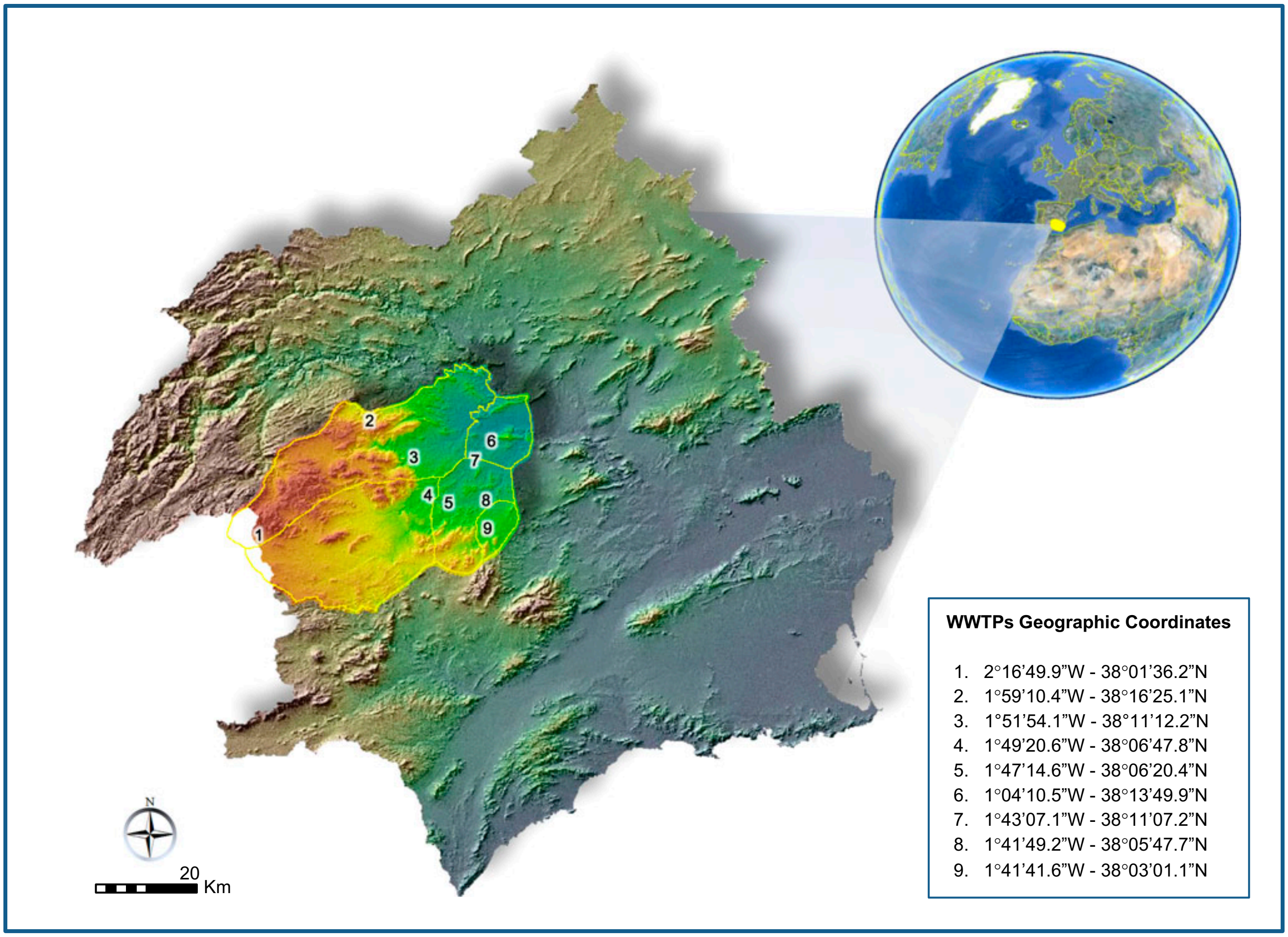

Fig. 1. Location map for the Public Water Authority for the Segura River with the study area. Numbers represent the different WWTPs: (1) Cañada de la Cruz, (2) Benizar, (3) Moratalla, (4) Caravaca de la Cruz, (5) Cehegín, (6) Calasparra, (7) Valentín, (8) El Chaparral, and (9) Bullas.

causing a water deficit. The predominant types of soil are calcareous soils (Lepthosols) in two-thirds of the region, and marls on the Xerosols.

Agricultural land occupying around 28% (8% irrigated) of the total study area (Fig. 2), is mainly located on calcareous soils at medium altitude, with aquifer resources present and consists of herbaceous crops (70%) and woody crops (30%) [20].

Eight groundwater bodies were identified in the study area, with a total area of 355,257 ha [2]. The groundwater level depths of each aquifer were obtained from data provided by the piezometric monitoring network in the Hydrological Plan of the Segura Basin. This network consists of 230 piezometric control points distributed across the basin groundwater bodies [2]. In the study area 49 piezometers were identified, providing the water level data or pressure in the different aquifers.

2.2. Monitoring of reclaimed water

Nine WWTPs were identified in the study area (Bullas, Calasparra, Caravaca, Cehegín, Valentín, Chaparral, Moratalla, Benizar, Cañada de la Cruz). A 12 month monitoring campaign (January 2012–December 2012) was setup in each of the WWTPs located in the study area. Four samples from each water source were collected in glass and plastic bottles, transported in an ice chest to the laboratory, and stored at 5°C before being processed for chemical analysis.

The electrical conductivity (EC) and pH were determined using a multi-parameter EC meter and turbidity was measured with a Dinko-D-110 (Dinko Instruments S.A., Barcelona, Spain) turbidity meter. The chemical oxygen demand (COD) was determined with cuvette test LCK 614 (50–300 mg L^{-1}), following the standard DIN 38409-4 and using a CADAS 50 UV-vis spectrophotometer (HACH-LANGE, Germany). The biological

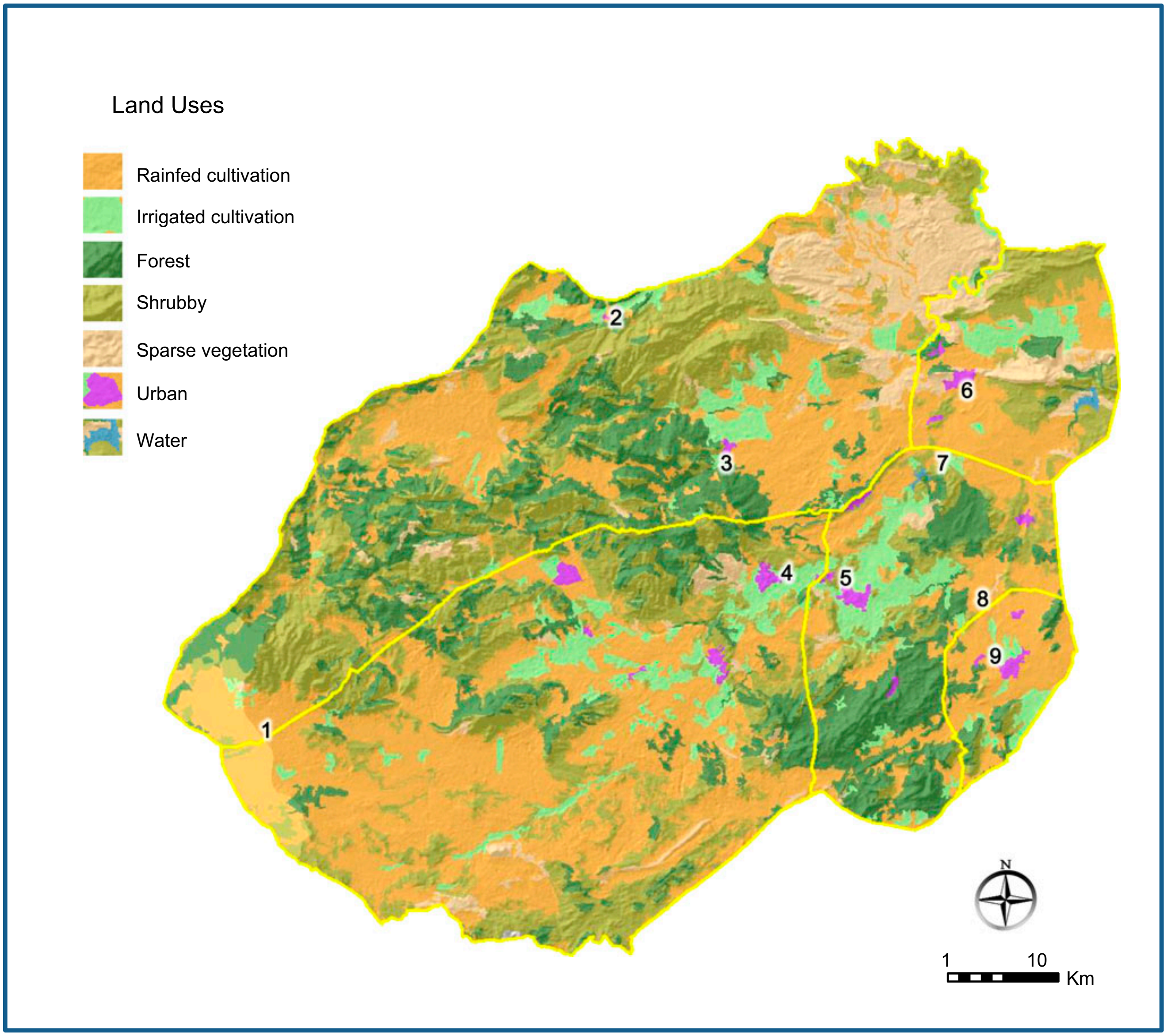

Fig. 2. Land use thematic map used to evaluate the potential land use of the study area.

oxygen demand (BOD_5) and total suspension solids (TSS) were determined according to the 5210B, 2540D, and 2540E standards, respectively, of the Standard Methods [17]. Total nitrogen (TN) and total phosphorus (TP) were obtained using the cuvette tests LCK 138 (1–16 mg TN L^{-1}), LCK 238 (5–40 mg TN L^{-1}), LCK 303 (2–47 mg NH_4-N L^{-1}), and LCK 350 (2–20 mg TP L^{-1}), following the 2,6-dimethylphenol method (TN, APHA-AWWA-WEF, 1999), the standard DIN 38406-E 5–1 (NH_4-N), and the standard DIN 38405-D11–4 (TP), respectively, and using the same spectrometer. For concentrations higher than the upper limits of the cuvette tests, the samples were diluted previously.

The microbiological quality of the water destined for irrigation was assessed by the detection of *E. coli*, by a membrane filtration procedure [21]. Samples were filtered under vacuum through sterile, 0.45 µm-pore-size membrane filters (Millipore, Billerica, USA). The filtrates were plated onto Chromocult agar plates (Merck, Darmstadt, Germany), incubated for 24 h, and assessed. The incubation temperature was 37°C. The helminth eggs (HE) were measured by following Bailenger's method [22].

2.3. Criteria for the identification of areas suitable for aquifer recharge

This step included the identification of the sites with potential for aquifer recharge, taking into account exclusion criteria (economic, environmental, and technical constraints) as well as the quality of the reclaimed water from the WWTPs of the study area. The economic criteria included affordability and the cost of adduction and pumping devices. The environmental criteria covered urban agglomerates and water resources vulnerability. The technical criteria included soil and groundwater characteristics, groundwater level depth, slope, land use, soil texture, road access, infiltration rate, and the distances between the WWTPs and the infiltration sites. The criteria selected for the different variables were based on information published in international guidelines and studies [6,23–28].

2.3.1. Economic criteria

The economic criteria included the cost of water transfer from the WWTPs to the infiltration sites (infiltration basins). As stated by the EPA [25], the main criteria should be the transport distance from the WWTP to the potential application site, which should not exceed 8 km, and the costs associated with the pumping systems, for which the elevation difference should not exceed 15 m. An area no more than 8 km away from the WWTP and with less than 15 m elevation difference was defined suitable for the transport of reclaimed water (from the WWTP of each village).

2.3.2. Environmental criteria

The environmental criteria considered three variables: distance from water supply sources (reservoirs, streams, and potable wells), urban agglomerations, and natural ecological reserves. A buffer area of 200 m around urban agglomerations and tourist areas was defined in order to avoid direct contact of the reclaimed water with the population and livestock. Finally, since it was impossible to perform a hydrogeological study which would provide less uncertainty, buffer areas of 500 m around water reservoirs and of 100 m around wells and streams (for water consumption or irrigation) were defined, to avoid their contamination by the infiltration of reclaimed water. Areas classified as ecological reserves were also excluded.

2.3.3. Technical criteria

For the technical criteria, six variables were considered:

Land use: the CORINE Land Cover database [29] was used to evaluate the potential land use of the studied area.

Slope: infiltration–percolation sites should preferably be constructed on slopes ranging from 0 to 12%. Higher gradients increase runoff, soil erosion, and therefore soil instability, which risks basin safety and increases refilling costs [25]. Steeper areas and rocky areas would not be suitable economically, since they would lead to high excavation costs.

Soil texture: infiltration basins should be located in sandy loam, loamy sand, or fine sand soils that are permeable enough to allow high infiltration rates and to enhance the removal of trace organics, nutrients, heavy metals, and pathogens [25,27]. To minimize soil clogging and to ensure the final purification of the reclaimed water, the soil must have a clay fraction of no more than 10% [25]. Therefore, soils with more than 10% clay were not included.

Groundwater level depth: aquifers should be sufficiently deep and transmissive to prevent excessive increases of the groundwater table due to infiltration. The minimum static groundwater level acceptable for reclaimed water infiltration is 5 m below the surface, in order to have a sufficient vadose zone for the final purification [6,23].

Roads: road access to the infiltration sites allows quick maintenance and operation of the basins. Therefore, sites located more than 50 m from a road were excluded.

2.4. Data analysis

Analysis of geographical data was performed using the software ArcGIS 10 (ESRI, USA), with ArcCatalog, ArcMap, and ArcScene applications. This work involved the confirmation of information obtained in field visits and the development of a geographical model that assumes criteria for the identification of areas suitable for aquifer recharge.

A suitability map with areas for aquifer recharge was generated from the thematic and basic information maps described in Table 1. After this process, the areas with soil properties more suitable for reclaimed water infiltration were evaluated, since this is an important factor for aquifer recharge [25].

Spatial analysis was carried out through the representation of each selected variable by a thematic layer (thematic map). The thematic layers were developed

Table 1
Basic information maps used in the representation of each selected variable by a thematic map to get the optimal recharge area for groundwater infiltration

Attributes	Description	Source
Digital elevation model (DEM)	3D representation of a terrain's surface with elevation data. (pixel resolution 10 m)	National Geographic Institute (IGN)
Slope map	The maximum change in elevation (degrees). (pixel resolution 10 m)	Own elaboration, based on DEM data
Soil texture	Soil texture map using FAO classification. (pixel resolution 30 m)	Own elaboration, based on several data
Soil	LUCDEME project (1986). Soil map, scale 1:100,000	Ministry of Agriculture
Lithology	Lithologic map extracted from geological mapping MAGNA, 1:50,000 scale	Geological and Mining Institute of Spain (IGME)
Drainage network	Streams bed map from Segura river basin, 1:5,000 scale	Mapping Service Region of Murcia
Road network	Regional roads map, 1:5,000 scale	Mapping Service Region of Murcia
Urban population	Urban population area map. CORINE Land Cover (2006). 1:100,000 scale	European Environment Agency (EEA)
Ecological reserve	Map of Natura 2000 network of Region of Murcia, 1:50,000 scale	Ministry of Agriculture
Land use	Coverage and land use map. CORINE Land Cover (2006). 1:100,000 scale	European Environment Agency (EEA)
Aquifers masses	Aquifers masses map of Segura river basin, 1:100,000 scale	Confederación Hidrográfica del Segura (CHS)
Groundwater depth	Groundwater depth map, using piezometer information data from CHS	Own elaboration, based on piezometer data

from geographical data obtained from official sources, and layers with vectorial information were rasterized for subsequent analysis. Each pixel (cells representing 10 m × 10 m) in each layer was assigned a digital number containing the information data of the layer. Map algebra was used to carry out operations between grid cells of different thematic maps, in order to generate a final suitability map for the infiltration of reclaimed water. The study of soil permeability is one of the most important elements in the analysis because this process will determine the levels of infiltration [30]. The permeability was assessed using textural values calculated from data obtained by the physical modeling of soil properties using environmental variables [31]. Values of textural fractions (clay, silt, and sand) were used to obtain the areas of optimal permeability.

These values, in addition to the optimum groundwater depth, were the main variables of the technical criteria. However, the inability to use additional information (ETo, precipitation, groundwater extraction) in places where the piezometric data are available has prevented the application of predictive models of groundwater levels [32,33]. Therefore, the aquifer data were processed using "Kriging" [34], an interpolation technique which uses a geostatistical point estimation method, based on the premise that the groundwater spatial variation of the masses follows homogeneous patterns [35]. This solution does not provide the best results, but to a substantial degree allows the determination of areas with piezometric values optimal for the discharge of reclaimed water.

3. Results and discussion

3.1. Study area

The total area assessed was 237,960 ha. This area is divided into five main municipalities, where land used for agriculture (rain-fed and irrigated) represents 44% of the total area and forestry 19% (Fig. 2). In the study area there are nine WWTPs (Bullas, Calasparra, Caravaca, Cehegín, Moratalla, Valentín, Chaparral, Benizar, Cañada), four of them without tertiary treatment (Valentín, Chaparral, Benizar, Cañada). The good condition of urban wastewater in the Region of Murcia usually facilitates its biological treatment. The general approach for "Secondary Treatment" is based on the biological purification of activated sludge (as in Caravaca, Cehegín, Moratalla, Valentín, Chaparral, Benizar, and Cañada). One of its advantages is the creation of high-performance compact installations specialized in the removal of organic pollutants [7].

In Murcia, there has been a gradual implementation of "Tertiary Treatments" aimed at disinfecting and improving the health guarantees of reused water [7]. The most used disinfection process is ultraviolet radiation: (as in Caravaca, Cehegín, and Moratalla) although an additional chlorination labyrinth is always used, even a maturation pond (Bullas) for natural disinfection is used in some cases [36]. Due to the specificities of certain locations, some treatments include the use of membrane biological reactors (MBR) (Calasparra) [5].

Table 2 shows the main characteristics of the nine WWTPs located in the study area; although for this study only five WWTPs were selected—those which satisfied the technical and economic criterion of an annual volume treated in excess of 500,000 m^3 (Bullas, Calasparra, Caravaca, Cehegín, and Moratalla).

3.2. Analysis of the reclaimed water

The characteristics of the different effluents monitored during the 12 months are shown in Table 3. The reclaimed water did not present soil salinity risks since the EC values were between 1.4 and 2.1 dS m^{-1} in the acceptable range based on Food and Agriculture Organization (FAO) standards [23]. Short-term agronomic studies on the effects of reclaimed water on soil demonstrated no impacts with regard to salinity [37,38] or heavy metal accumulation in soil [39], but long-term studies found soil salinity increases of 2–3-fold after 11 years of application of reclaimed irrigation water to an agricultural soil [40] and to golf course soils [41]. Therefore, regular monitoring of the site-specific water and soil and appropriate management are needed to mitigate the negative impacts of sodium and salts accumulation [38,41].

The sodium adsorption ratio (SAR) was estimated by considering the average concentrations of Na and Ca in the reclaimed water and the value of Mg [27,28,42]. The values ranged between 5.4 in Caravaca and 6.9 in Moratalla; this shows, according to the data reported by Ayers and Westcot [43], that these soils have a moderate risk of sodification in the long-term if reclaimed irrigation water is used. This problem is mainly related to a relatively high Na concentration (between 172 in Cehegin and 346 mg L^{-1} in Bullas) and low Ca and Mg concentrations (58–96 and 35–91 mg L^{-1}, respectively). According to Ganjecunte et al. [44], to prevent these problems and avoid deterioration of the soil physical properties, periodic flushing of salts with fresh water is needed. The heavy metal concentrations (Co, Ni, Pb, Cr, Zn, and Cd) were also below the toxic levels (<0.05, <0.20, <5, <0.10, <2, and 0.01 mg L^{-1}, respectively), according to Ayers and Westcot [43].

In dry and semi-arid conditions, as in the Region of Murcia, Mediterranean soils often show low levels of organic matter at the soil surface that, in some cases, may favor the onset of land degradation processes [45]. Therefore, the organic matter in the reclaimed water could contribute to an improvement of the soil organic carbon content [46] in low-fertility soils [47]. Part of the organic matter will be

Table 2
Main characteristics of the nine WWTPs localized in the studied area with different treatments used; maturation pond (MP), activated sludge (AS), ultraviolet (UV), and membrane bioreactor (MBR); Annual volume treated (m^3) and the use of the wastewater, direct and indirect reuse (%)

WWTP treatment		Annual volume treated	Direct reuse	Indirect reuse (infiltration)	% Reuse indirect (discharge to channel)	Channel, aquifer or irrigation area
Bullas	MP	1,215,468	90%		10%	Norwest irrigation area/Los Muletos watercourse
Calasparra	MBR	654,550			100%	Argos river
Caravaca	AS + UV	1,666,995	70%		30%	Norwest irrigation area/Rio Argos
Cehegín	AS + UV	973,437	100%			Norwest irrigation area
Valentín	AS	58,984			100%	Argos river
El Chaparral	AS	9.03	50%		50%	Norwest irrigation area
Moratalla	AS + UV	642,371			100%	Benamor River
Benizar	AS	48,471			100%	Benizar creek
Cañada	AS	23,004		100%		No underlying aquifer

Table 3
Water quality analysis of the different WWTPs during 2012. EC, total nitrogen (N_t), total phosphorus (P_t), TSS, biological oxygen demand (BOD_5), COD, turbidity (NTU), E.coli, and Helmint eggs (eggs 10 L^{-1})

WWTP units	EC ($dS\,m^{-1}$)	Nt ($mg\,L^{-1}$)	Pt ($mg\,L^{-1}$)	Turbidity (NTU)	SAR	TSS ($mg\,L^{-1}$)	BOD_5 ($mg\,L^{-1}$)	COD ($mg\,L^{-1}$)	*E. coli* (ufc 100 mL^{-1})	Helmint eggs (eggs 10 L^{-1})
Bullas	2.1 ± 0.3	9.6 ± 3.1	2.4 ± 0.7	20.0 ± 5.8	5.8 ± 0.6	32.7 ± 9.9	5.2 ± 2.5	43.2 ± 11.8	151.0 ± 12.1	<1
Caravaca	1.8 ± 0.2	4.7 ± 1.1	1.4 ± 0.6	2.6 ± 1.2	5.4 ± 0.3	4.1 ± 1.9	2.3 ± 0.7	25.3 ± 8.3	102.0 ± 21.5	<1
Cehegín	1.4 ± 0.3	9.4 ± 3.5	0.9 ± 0.5	3.5 ± 1.2	5.9 ± 0.7	5.2 ± 2.0	3.9 ± 2.1	30.7 ± 10.9	74.8 ± 10.4	<1
Moratalla	1.5 ± 0.3	7.1 ± 7.2	3.3 ± 4.1	5.2 ± 4.7	6.9 ± 1.2	11.2 ± 1.5	8.0 ± 1.9	40.1 ± 25.9	235.4 ± 34.5	<1
Calasparra	1.4 ± 0.4	5.3 ± 1.8	1.5 ± 0.3	2.2 ± 2.5	6.2 ± 0.6	5.0 ± 0.5	5.6 ± 1.8	23.7 ± 8.2	1.5 ± 0.0	<1

incorporated into the soil, but a significant part of the dissolved organic carbon (typically 20–2 $mg\,L^{-1}$) will be oxidized by soil bacteria [28].

The nitrogen concentration (4.7–9.6 $mg\,L^{-1}$) was very low and most of the ammonia will be oxidized to nitrite and nitrate due to nitrification in the upper layers of the soil. In the lower layers, nitrite and nitrate will be reduced to nitrogen gas due to denitrification.

Nitrogen is taken up by plants as nitrate (NO_3^-) and ammonium (NH_4^+). Most of the N in the soil is in the organic fraction, and is not available to plants. The availability of organic N is determined by different processes such as mineralization (which is due to the activity of microorganisms), denitrification, and leaching. Therefore, the soil will act as a "treatment" in the removal of ammonia, nitrite, and nitrate. Phosphorus, present in the reclaimed water at very low concentrations (0.9–3.3 $mg\,L^{-1}$), will enter the soil in mineral forms, which tend to be retained by mineral colloids or to form phosphates (e.g. of calcium, aluminum, and iron) with low solubility. Plants take up phosphorus from the soil solution as the orthophosphate ion: $H_2PO_4^-$ or HPO_4^{2-}. The form in which phosphorus is taken up is pH-dependent: at higher pH, the predominant form is HPO_4^{2-}.

The BOD_5 and COD concentrations (2.3–8 and 23–40 $mg\,L^{-1}$, respectively) showed the performances of the different WWTPs to be excellent. The good condition of the urban wastewater in the Region of Murcia usually facilitates its biological treatment, and it meets the reference effluent limits: 25 $mg\,L^{-1}$ BOD_5 and 125 $mg\,L^{-1}$ COD (Directive 91/271/EEC).

Regarding the microbiological quality, the HE and *E. coli* were always below the thresholds (<10 eggs 10 L^{-1} and 10,000 cfu 100 mL^{-1}, respectively, for indirect infiltration use) imposed by Royal Decree-Law 1620/2007, which regulates the use of reclaimed water in Spain. This result is in accordance with previous studies carried out in Murcia [12], which concluded that, for 43 WWTP effluent samples analyzed, nematode eggs were absent in 79% of the water samples receiving secondary treatment and completely absent in the WWTP effluents that had undergone tertiary treatment.

In soil aquifer treatment (SAT), microbial adhesion has two aspects: biofilm formation and virus/pathogen removal [48]; in general, there is a 4–6 log removal of microorganisms, such as F-specific RNA bacteriophages, enteric viruses, and total coliforms (WHO, 2006). Many researchers have reported that natural purification systems are capable of removing microbial pathogens and viruses [49–51]. Guessab et al. [52] observed removal efficiencies of up to 99.9% for fecal coliforms and fecal streptococci in an infiltration–percolation system and complete elimination of helminth and cestode eggs, for a hydraulic loading rate (HLR) of up to 0.23 $m\,d^{-1}$. Brissaud et al. [53] observed the 1.5–4-log removal of fecal coliforms in sand columns, for an HLR of 0.5 $m\,d^{-1}$. Therefore, although SAT can act as a tertiary treatment, monitoring programs for reclaimed water infiltration must be setup using a conservative approach (i.e. with intensive monitoring of groundwater quality) in order to evaluate the effectiveness of the SAT.

3.3. Optimal areas for infiltration

Due to the regional division into municipalities, it was decided to establish the potential recharge areas by municipality. Therefore, each WWTP is located in a distinct municipality (Bullas, Calasparra, Caravaca, Cehegín, and Moratalla). The technical and environmental criteria data refer to the municipality surface areas, and the economic criteria data refer to an 8 km radius around each WWTP.

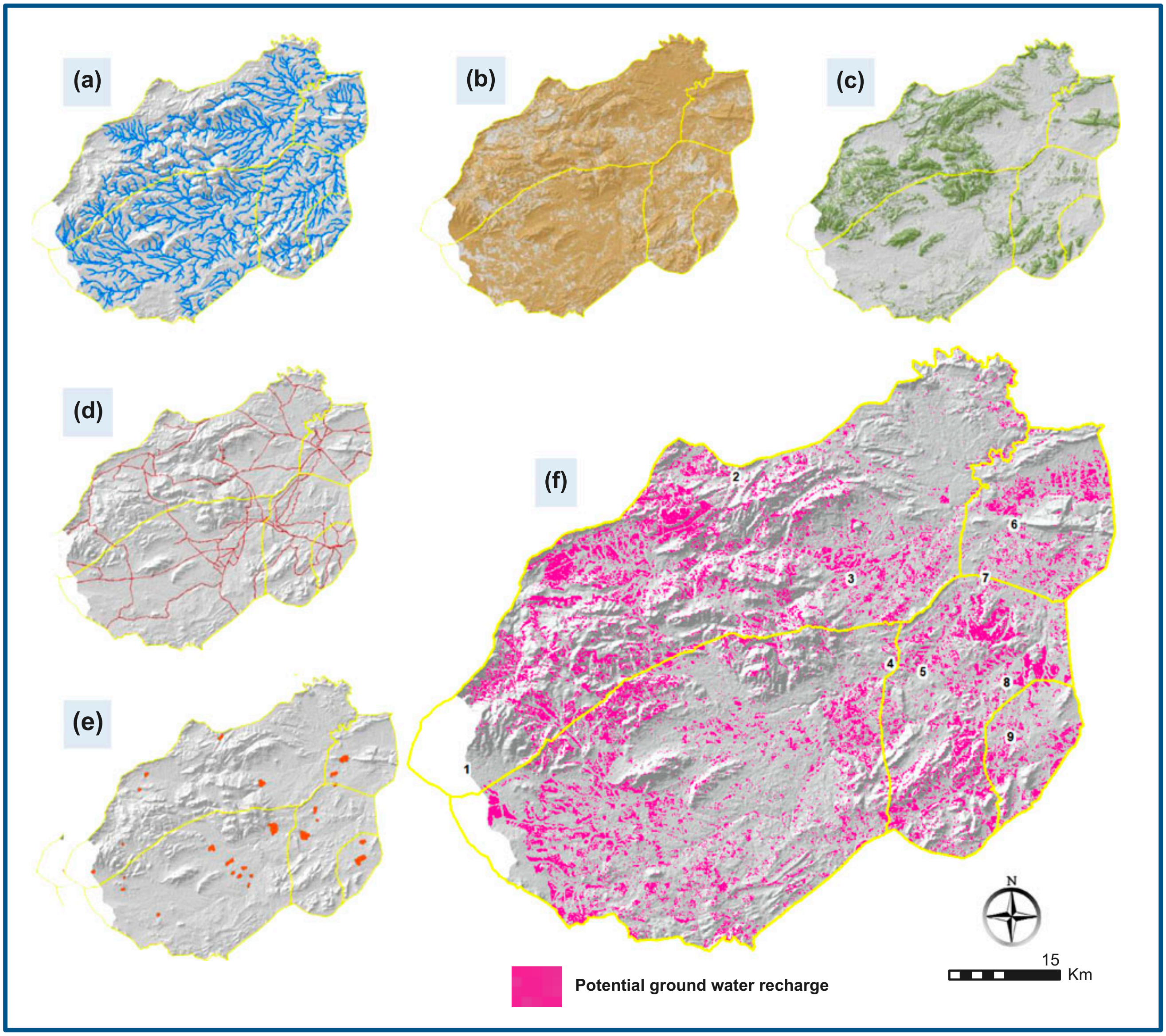

Fig. 3. Technical and environmental criteria. (a) Hydrographic network, (b) Textures, (c) Slope, (d) Main road network, (e) Urban areas, and (f) Potential groundwater recharge.

Table 4
Technical and environmental criteria referenced to each municipality surface, urban areas, water supply network, roads, slope and texture. Potential recharge areas after technical and environmental criteria

Municipalities	Surface (ha)	Urban áreas (%)	Water supply network (%)	Roads (%)	Slope (%)	Texture (%)	Potential recharge areas (ha)	Potential recharge areas (%)
Bullas	8,223.9	8.5	25.0	8.2	12.2	66.8	2,276.1	27.6
Calasparra	18,618.4	2.5	25.4	3.9	16.3	74.5	2,617.3	14.0
Caravaca	85,989.8	1.4	23.7	2.6	16.3	68.2	12,002.5	13.9
Cehegin	30,032.5	2.3	25.5	4.0	20.8	60.4	5,973.5	19.8
Moratalla	95,095.4	0.5	18.4	2.5	32.3	60.7	14,100.7	14.8

Table 5
Economic criteria with the 8 km perimeter buffer as reference surface. Optimal recharge area referenced to 8 km buffer including technical and environmental criteria. Elevation and road network

Municipalities	8 km perimeter buffer (ha)	Potential recharge area (ha)	Potential recharge area (%)	Elevation (%)	Road network (%)	Optimal recharge area (ha)	Optimal recharge area (%)
Bullas	20,105.8	4,465.9	22.2	10.1	1.9	2,019.7	10
Calasparra	20,105.8	2,457.7	12.2	5.7	0.9	1,109.8	5.5
Caravaca	20,105.8	3,662.8	18.2	11.0	1.6	1,122.3	5.5
Cehegin	20,105.8	3,870.5	19.2	13.8	0.7	946.7	4.7
Moratalla	20,105.8	2,933.8	14.5	7.1	1.2	1,243.4	6.1

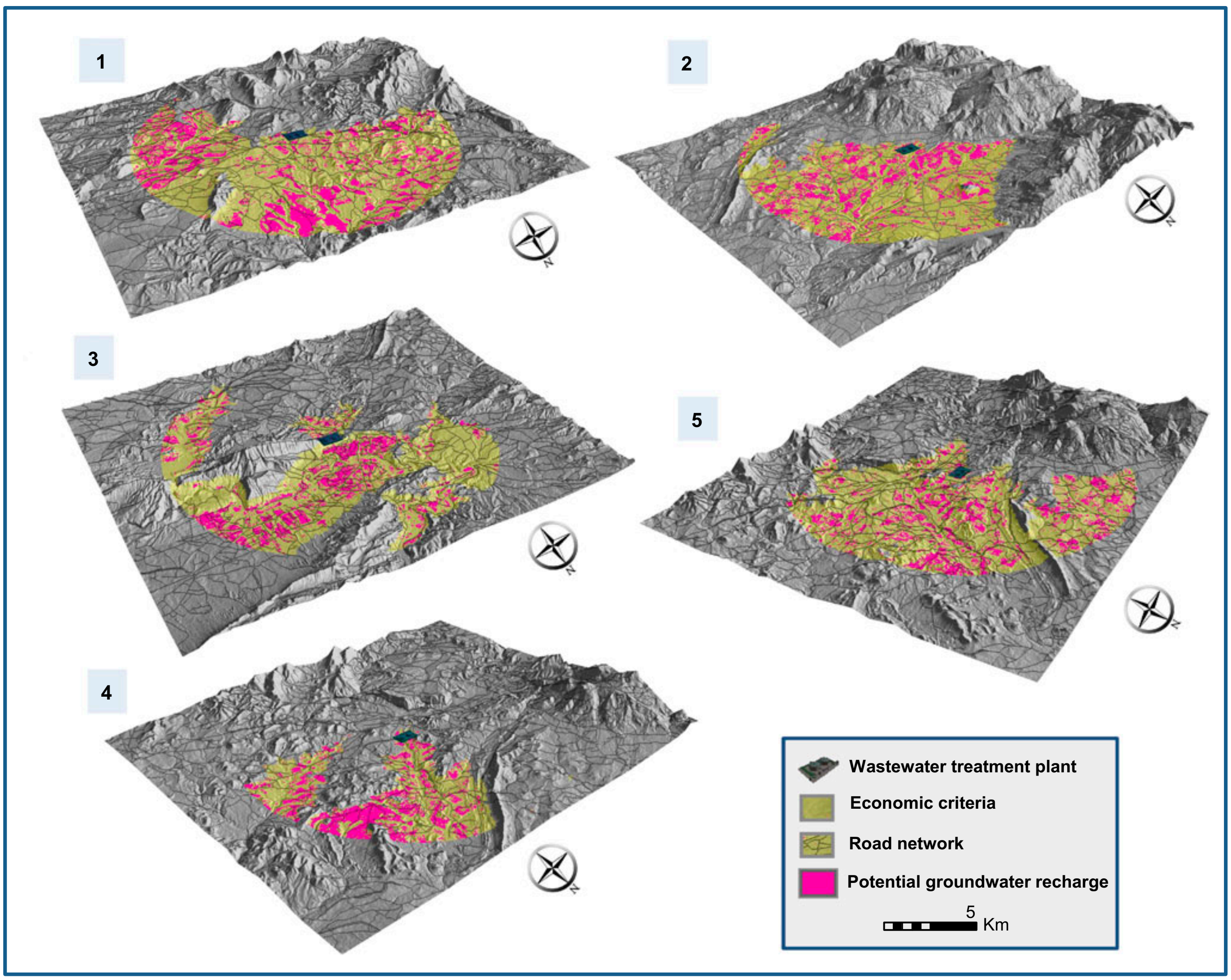

Fig. 4. Technical, environmental, and economic criteria in each WWTP: (1) Bullas, (2) Moratalla, (3) Calasparra, (4) Cehegín, and (5) Caravaca.

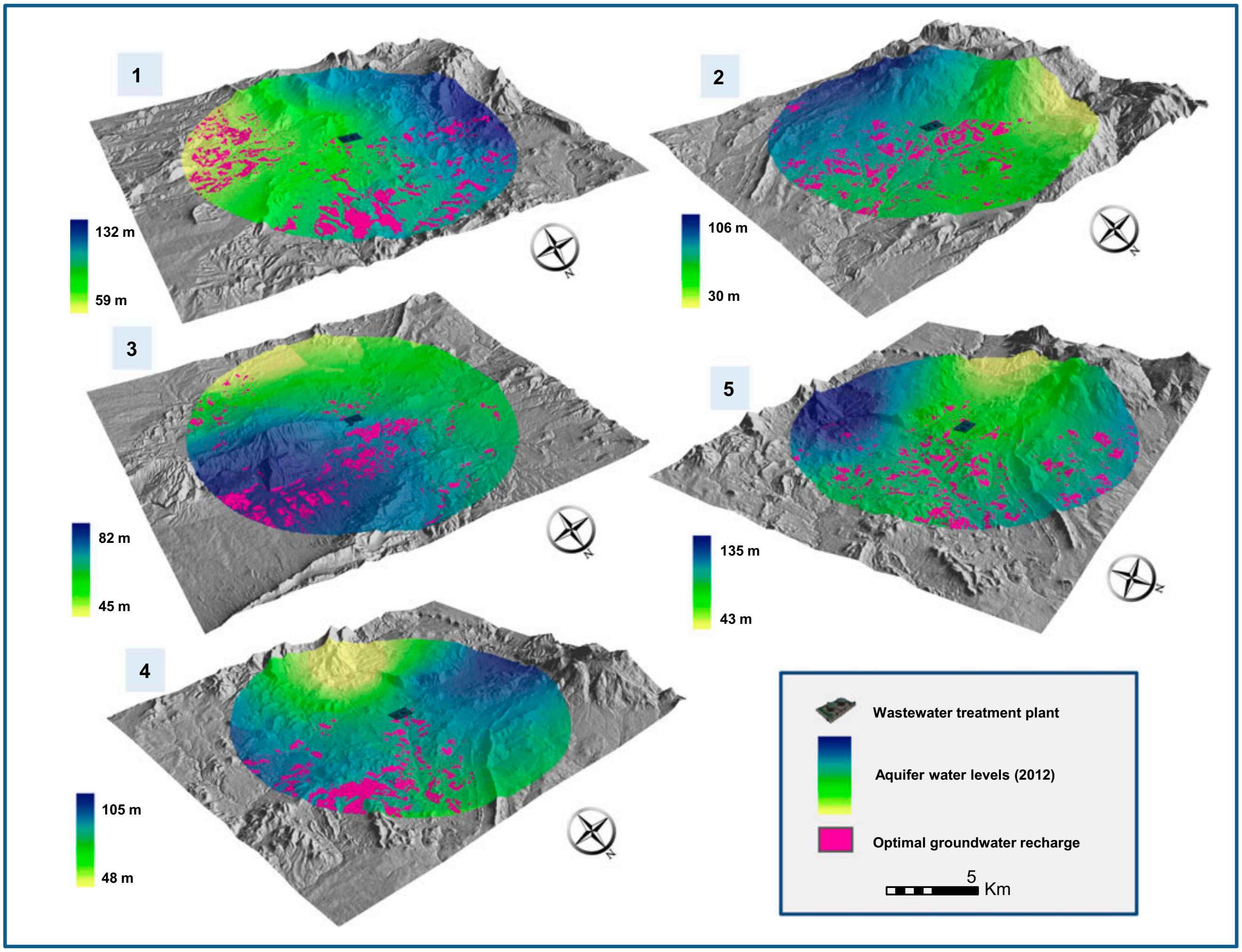

Fig. 5. Optimal recharge area with the aquifer depth for each WWTP: (1) Bullas, (2) Moratalla, (3) Calasparra, (4) Cehegín, and (5) Caravaca.

The environmental criteria were divided into two thematic maps: urban areas and the hydrographic network. The urban areas thematic map was obtained by creating a buffer area with a 200 m radius around villages, house agglomerations, and isolated houses (coded as 0), as shown in Fig. 3. The urban areas were dispersed in all the municipalities and never reached more than 10% of the total area, because of the rural character of the area (Table 4). The criteria for the hydrographic network thematic map were based on a buffer area of less than 100 m radius for streams and wells and less than 500 m radius for reservoirs, both coded as 0 (Fig. 3). The water supply sources were similar in all the municipalities; the range was between 18 and 25% (Table 4).

The technical criteria were divided into three thematic maps: slope, textures, and main road network. In order to define the slope thematic map, the study area was first clipped and reclassified into two categories: one with values less than 12% (coded as 1) and another with higher values (coded as 0) (Fig. 3). The study area was irregular, with hills having moderate altitudes ranging from 218 to 845 m. The most restrictive municipality was Moratalla (32%) and the least restrictive was Bullas (12%) (Table 4). The texture thematic map was defined by clipping all polygons with a very low clay fraction (sandy loam, loamy sand, fine sand) (Fig. 3). Texture was the most restrictive technical criterion, with a range of 60–74% (Table 4). The main roads network thematic maps were developed with the sites located more than 50 m from roads (Fig. 3).

The economic criteria were divided into three thematic maps. A buffer area of 8 km radius around each

WWTP (coded as 0), the elevation thematic map reclassified into two categories: one with elevation values less than 15 m (coded as 1) and another with higher values (coded as 0), and the last thematic map, distance to the road network not more than 50 m. The 8 km radius around each WWTP was taken as a reference to calculate the other economic criteria (Table 5). The potential groundwater recharge area according to the technical, environmental, and economic criteria is represented in Fig. 4.

The optimal recharge area and the technical criterion groundwater depth are represented in Fig. 5. The lowest groundwater depth of all the WWTPs was 30 m and the water treatment is assured in the five WWTPs, because the groundwater table was deeper than 5 m in all cases (Fig. 5). The final potential area for reclaimed water infiltration around each WWTP is shown in Table 5. The greatest surface area for infiltration corresponded to Bullas, with 2,020 ha (24.5%) of the total area studied (8,224 ha). The most restrictive variable was the texture and availability of water supply sources, due to the presence of irregular terrain and water lines in the hydrographic basin of the study area (Table 4). After analyzing all the criteria established of the total area studied (237,960 ha), only 2.7% (6,442 ha) can be considered optimal for aquifer recharge.

4. Conclusions

Optimal areas for groundwater recharge with reclaimed water were identified in the northwest of the Region of Murcia using GIS-based multi-criteria analysis, hence validating and demonstrating an innovative management system for the optimization of the use of the reclaimed water. Technical, environmental, and economic criteria were setup, which allowed the construction of thematic maps. The application of this GIS multi-criteria analysis gave a final, optimal map showing areas (6,442 ha) appropriate for reclaimed water infiltration.

This work will contribute to the optimization of the existing water resources in the Region of Murcia, improving discharge management, reducing the overexploitation of aquifers, and providing a new tool for their sustainable management. From the economic point of view, the use of reclaimed water for aquifer recharge during periods of low water demand reduces the operating costs of the WWTPs—by decreasing their energy costs and, in some cases, by providing alternative systems for the tertiary treatments.

GIS analysis has been shown as a valuable tool in the integrated management of the scarce water resources in semi-arid areas, which are particularly affected during drought periods and are vulnerable to the reduction in rainfall foreseen by climate change scenarios.

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