ELSEVIER

Desalination 188 (2006) 69–77

DESALINATION

www.elsevier.com/locate/desal

Using electrical imaging for assessing suitability of reclaimed water recharge at Begur, Spain

J.C. Tapias[a*], M. Himi[b], A. Masachs[a,b], C. Nieto[c], F. Brissaud[d], M. Salgot[a], A. Casas[b]

[a]Department of Natural Products, Vegetal Biology and Soil Science, University of Barcelona,
Avda. Joan XXIII s/n. 08028, Barcelona, Spain
Tel. +34 (93) 402-4494; Fax: +34 (93) 402-4495; email: jtapias@ub.edu
[b]Department of Geochemistry, Petrology and Geological Prospecting, University of Barcelona,
c/. Martí i Franquès s/n. 08028, Barcelona, Spain
[c]Consorci de la Costa Brava, Plaça Josep Plà 4, 17001 Girona, Spain
[d]Hydrosciences, Maison des Sciences de l'Eau, Université Montpellier II, F-34095 Montpellier cedex 05, France

Received 15 November 2004; accepted 29 April 2005

Abstract

Groundwater is increasingly being used for water supply; however, the present social demand is not only to detect new groundwater resources but also to protect them. Moreover, reclaimed water is also a valued non-conventional resource. Both statements are especially true in arid and semi-arid areas where water is scarce, but also in the Mediterranean countries because of the wide rainfall irregularity. When trying to perform an integrated management of water resources, groundwater volumes can be increased by reusing reclaimed water for recharge. Surface spreading is the simplest, oldest, and most widely applied method of artificial recharge. Wherever it goes, water remains in some part of the hydrologic cycle, but what is really desired when discharging or reusing wastewater is to prevent the effluent — or more correctly, the pollutants it contains — from causing water quality and public health concerns. When recharging with reclaimed effluents, to ensure an effective percolation through the soil and an adequate treatment of the effluent, the structure and properties of the vadose zone must be understood in detail. One of the easiest and cost-effective techniques for producing a large amount of information on aquifer geometry and subsoil properties is the electrical imaging technique. The underlying objective was to test the advantage of using this geophysical method for the continuous characterization of subsoil structure around the Begur treatment plant where treated wastewater is discharged and reused in a soil–plant–aquifer system. The good results of wastewater application in the area are also discussed.

Keywords: Plant–soil–aquifer treatment; Water infiltration; Groundwater recharge; Electrical imaging

---

[*]Corresponding author.

Presented at the International Conference on Integrated Concepts on Water Recycling, Wollongong, NSW, Australia, 14–17 February 2005.

1. Introduction

Reclaimed water is an evermore valued non-conventional water resource. This is especially true in the arid and semi-arid zones of the earth where water is scarce, but also in the Mediterranean countries because of the wide rainfall irregularity. Among the possibilities of wastewater reuse, groundwater recharge is one of the most promising [1]. Where hydrogeological conditions are favourable, wastewater reclamation can be implemented in a simple way by the soil–aquifer treatment (SAT) process. As wastewater percolates through the vadose zone, and then some distance laterally through the aquifer, additional treatment is provided to the water, mainly through filtration processes.

At present, some concerns regarding health risk considerations have limited the expanding use of reclaimed municipal water for groundwater recharge, especially if a large portion of the aquifer contains reclaimed water that may enter the domestic water supply [2]. The SAT process should be designed and managed to avoid encroachment into the native groundwater and to use only a portion of the aquifer. The distance between infiltration basins and wells should be as great as possible, usually at least 50–100 m and transit (residence) time must last from 3 to 6 months to give adequate treatment.

The ability of the subsoil and bedrock to treat pollutants adequately depends on the geological and hydrogeological characteristics of the site, particularly the permeability (including the soil one), the thickness of the subsoil and the depth to the water table. As reclaimed water migrates from the land surface, it first moves through an unsaturated zone before recharging the saturated groundwater system. When water moves through the unsaturated zone (including soil), physical and chemical processes occur that can affect the water (and potential contaminants) volume and rate of movement. Aquifers associated with thick unsaturated zones (deep water tables) tend to have less recharge than aquifers with thinner unsaturated zones and water tends to move slowly in the first situation. Soil and subsoil provide the most effective protection of groundwater from pollution. Organic and clayey soils and clayey sands/gravels and permeable sands (i.e., combinations of sand, silt and clay) are the most suitable subsoils for effluent disposal and treatment. In contrast, once pollutants enter bedrock, the rate of purification declines. Groundwater is most vulnerable and at risk from pollution where bedrock, particularly limestone, is at or close to the surface: where clean, permeable sand/gravel underlies the site; and in sand/gravel where the water table is close to the surface. In areas with these conditions, pollution of wells is common.

Therefore, these pedological, geological and hydrogeological characteristics should be examined and mapped in detail, thereby providing a soil and subsoil assessment for any area or site. Modern geophysical methods, such as an electrical imaging system, can play an important role in these studies. For 2-D measurements, electrical imaging involves a large number of electrodes placed into the ground along a profile. The recorded apparent resistivities may then be used to construct a contour plot displaying the variation of resistivity both laterally and vertically over the cross-section since increasing separation between electrodes leads to greater depth penetration.

2. Begur wastewater treatment plant

The Begur wastewater treatment plant (WWTP) is located in the Empordà Basin (NE Spain), some 100 km north of Barcelona (Fig. 1). The coastal village of Begur (Girona Province, Spain) is a small tourist resort located at the top of a hill by the sea. Their WWTP processes domestic wastewater through a biological treatment using activated sludge. Their treatment capacity is about 500 m^3/d; but the seasonal

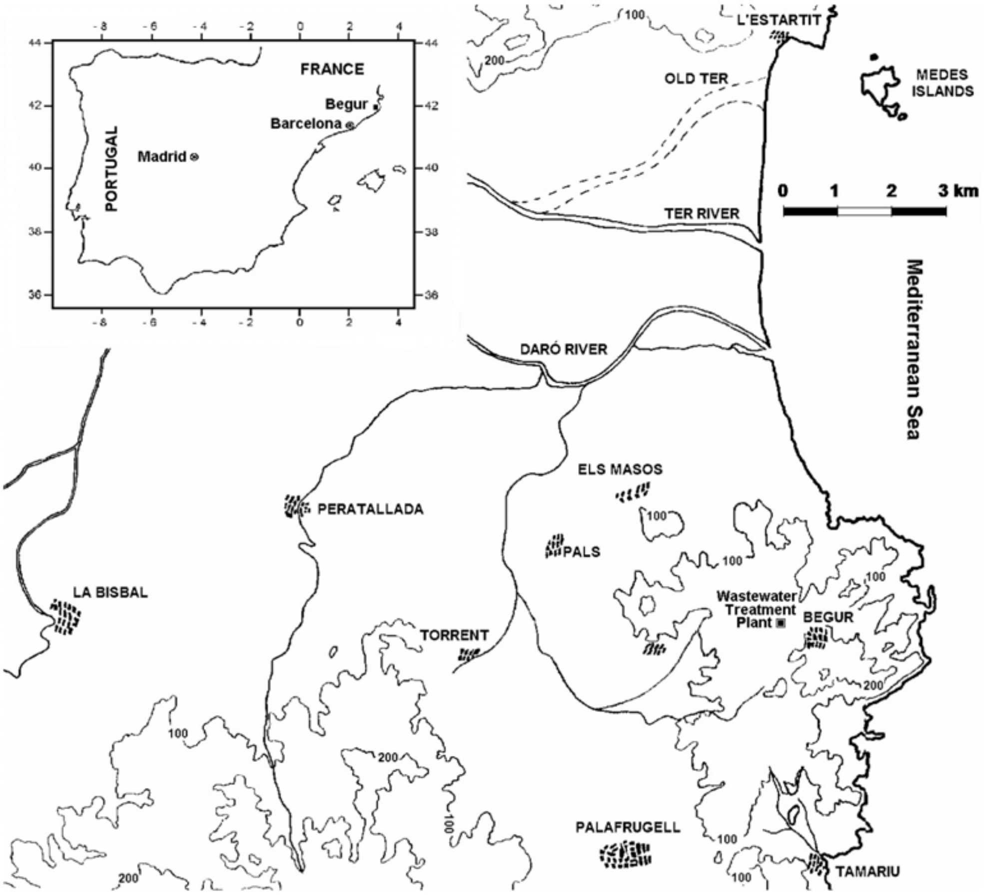

Fig. 1. Overview map of the area, with the location of the wastewater treatment plant near Begur.

variability must be pointed because population ranges from 500 equivalent-inhabitants in winter to more than 10,000 equivalent-inhabitants in summer. The effluent was monitored during several years, and physicochemical parameters and fecal coli-form were determined according to Standard Methods [3]. Coliphages F^+ and CN13 were detected and enumerated by the double-layer technique, and helminth eggs were determined according to the WHO method modified by Gaspard and Schwartzbrod [4]. The mean values for the physicochemical and microbiological parameters for the final effluent from the Begur WTP, present in Table 1, are in the usual range for a secondary effluent from a domestic WTP. The Begur WWTP has proved to be very effective in producing a high-quality secondary efflu-ent all year round: BOD_5 reduction from 230 to 5 mg/L, COD from 550 to 58 mg/L, and suspended solids from 280 to 7 mg/L. This effluent can be successfully used for irrigation, especially if soils are sandy and have high infiltration rates. The effluent does not add an excess of salts (Na^+) to the soil, avoiding changes in permeability, presence of anoxic zones and potential phytotoxic effects. As the secondary effluent of the WWTP fulfils the requirements of European Directive 91/271/CEE and WHO [5], groundwater recharge by surface spreading was considered [6].

The plant is located inland and separated from

Table 1
Characterization of the final effluent from the Begur WWTP (1995–2001)

Parameters	Effluent from WWTP Min	Avg	Max
pH	7.40	7.58	7.80
EC (µS/cm)	1710	2450	2800
COD (mg/L)	23	58	73
TOC (mg/L)	0.20	7.53	12.77
N-NTK (mg/L)	2.07	8.59	17.44
N-NH_4^+(mg/L)	2.02	7.20	16.52
N-NO_3^- (mg/L)	0.31	3.26	10.40
Na^+ (mg/L)	329	447	565
Ca^{2+} (mg/L)	80	145	185
K^+(mg/L)	14.25	26.52	44.80
Mg^{2+} (mg/L)	28	58	71
PO_4^{3-} (mg/L)	8.61	11.31	14.00
Fecal coliforms (log cfu/100 mL)	3.7	4.8	5.7
Somatic coliphages (log pfu/100mL)	3.5	4.1	4.8
F^+-bacteriophages (log pfu/100 mL)	2.8	3.4	4.3

the sea by a succession of small hills. Subsequently, its geographical and hydrological situation does not allow an easy disposal of the effluent generated by the plant. At the beginning, water infiltration through a 4-m-diameter well was planned. This design started in 1976 without any previous study, but the theory demonstrated that was completely insufficient to discharge sufficient water. Some days after operation commenced, the well became clogged and subsequently a plume of contaminated groundwater began to flown down-gradient. The soil characteristics of the zone let the water infiltrate naturally, but years after the lack of any management of the infiltration zone generated an "artificial wetland" that was a source of odours and insects, apart from the damage caused to the neighbouring pine plantations.

3. Geological context

From a geological point of view, the Begur massif, together with the Gavarres massif, constitute the uppermost part of the Catalan coastal ranges. Around the Begur WWTP two main sets of lithologies are recognized: Palaeozoic rocks and quaternary sediments.

Palaeozoic rocks are mainly constituted of Silurian schists and Cambrian dolomitized marbles. Silurian schists depict glossy appearance with greenish tones and, in addition, are affected by a dominant metamorphic foliation with "kink-bands" [6]. The disposition of schistosity planes shows in general a steeply-dipping cleavage. By their adjacent hand, dolomite marbles are grey rocks constituted by dolomite as the dominant mineral, with calcite and quartz as accessories. Stratification planes can be observed at some outcrops, but their global aspect is massive. The schistosity hardly affects these materials; however, they are intensively fractured by joints. Some quarries exploit these rocks near the treatment plant.

The quaternary sediments are mainly of aeolian origin, formed by well-sorted sands that built a set of dunes extending from the Pals beach to Tamariu. These are the younger sediments that overlay all the other existing lithologies. Field permeability tests of sand outcrops give values ranging between 1 and 6 cm/min. The rest of the quaternary sediments are colluvium deposits made up of red clays with boulders [8]. The WWTP is located near the sand dunes, but locally a less permeable clay layer underlies the sand and also the geometry of the impermeable basement (metamorphic schists and marbles) influences the recharge process (Fig. 2). With the aim of studying the recharge possibilities in mind, subsoil exploration was undertaken to define in detail the geological structure under the available surfaces.

4. Methodology

In order to assess thickness and lateral extent of the sand dunes, a 2-D resistivity survey was conducted. The resistivity method is based on measuring the potentials between one electrode

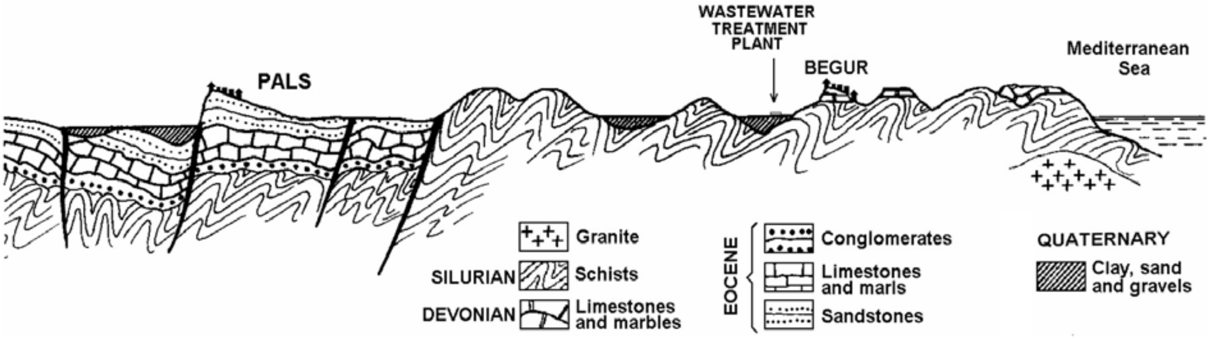

Fig. 2. Geological cross-section along the study area. The wastewater treatment plant is located on a valley filled by quaternary sediments overlaying the Paleozoic basement.

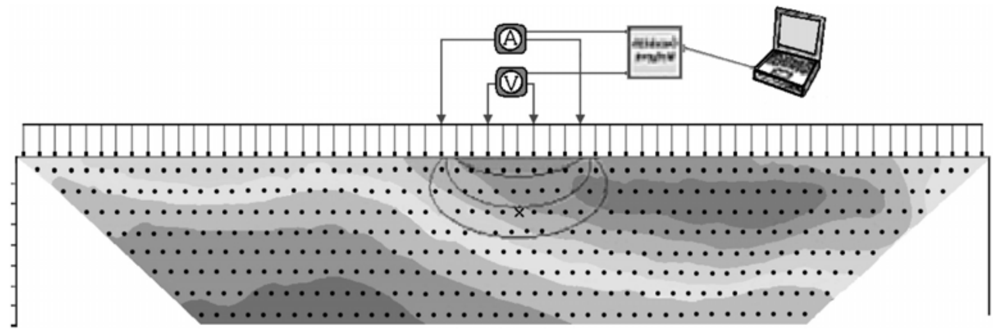

Fig. 3. Sketch of the computer-controlled multi-electrode system layout.

pair while transmitting DC between another electrode pair. The depth of penetration is proportional to the separation between the electrodes and by varying the electrode separation, information is provided on the subsoil stratification.

Several electrical imaging (EI) profiles were performed in the vicinity of the Begur WWTP. This geophysical technique can be considered the modern evolution of the classical geoelectrical methods, as the vertical electrical sounding and electrical trenching. In fact, the physical principle is the same, but in this case instead of using only four electrodes (two for energizing and two for measuring the potential generated), multiple electrodes that change function automatically are fixed in the soil surface (Fig. 3). All possible combinations of electrode pairs are considered, resulting in a data set of apparent resistivities at the so-called pseudo-depth at different locations [9].

Measurements were performed with the Syscal Junior multi-electrode system (Iris Instruments). The mixed Wenner-Schumberger array with 48 electrodes spaced 10 m apart was used for data collection in this study. Taking into account the extension of the emission line, this array allowed a maximum apparent depth of investigation of approximately 90 m.

The large amount of data produced by multi-electrode systems requires automated data handling and processing. Interpreting the resistivity data consists of three stages. The first in the production of an electrical image is the construction of a pseudo-section, an initial approximate image produced by plotting each recorded apparent resistivity. The second is the conversion of the observed data into an image of true depths and true formation resistivities by removing geometrical effects by a processes known as inversion. The third step is the geological interpretation of the resulting physical parameters.

The program RES2DINV [10] was used to invert the apparent resistivity values to a resistivity model section. In this method the subsurface is divided into cells of fixed dimensions for which the resistivities are adjusted iteratively until an acceptable agreement between the input data and the model responses is achieved, based on a non-lineal optimization technique by least-squares fitting [11]. During the inversion process, the root mean square (RMS) value of the difference between experimental data and updated model response was used as a criterion to assess the convergence at each iteration step. If the data error RMS value or the relative decrease of the data error RMS value drops below a pre-defined level, the inversion is said to converge and the process is terminated. Values of 2% and 0.01 were used as minimum values for data error RMS and minimum relative decrease of data error, respectively.

5. Wastewater application

Because of the problems caused by wastewater disposal in the described area, a solution was needed, and it was decided to use a soil–plant–aquifer treatment system (SPAT) — a modification of the classical SAT system — by using plants to increase the capacity of the system [12]. In a surface of 1.7 ha, 1200 poplar trees (*Populus* × *Euroamericana*) were planted (in three plots: I, II and III) in order to obtain a water loss by evapotranspiration and use the subsoil as a water reservoir for the tree water demand. Fourteen piezometers were installed in order to obtain samples of percolated water and detect the groundwater level [13]. The effluent was applied at a rate of 20–30 mm/d, and samples were taken from the piezometers holding water. The results are indicated in Tables 2 and 3. No studies were undertaken of the water detention time in the formation, and the recharged water was not recovered for any further use.

From the geological studies it was deduced that a thin (3–4 m depth) formation of sand dunes re-covered a small valley where groundwater did not exist in appreciable amounts and there are no wells to use such water. The conditions to use the small confined valley to test the capability of a SPAT system were ideal. It should be noted that six holes (2×2 m width and a large, 4-m depth) in different parts of the field were dug before the establishment of the system. The *in situ* observations are in agreement with the data obtained through the use of the electrical imaging method.

6. Discussion

The results of a standard smooth inversion on the recorded sections show well recognizable structures of high resistivities at shallow ranges and also at the bottom of the profiles. Therefore, the interpreted resistivity depth models suggest the existence of three broad electrostratigraphic layers. Nevertheless, the meanwhile classical inversion of geoelectric pseudo-sections, imposing smoothness on the resistivities, has some drawbacks in case of well defined structures with sharp resistivity contrasts, and for this reason a geological criteria must be established. By this kind of inversion distinct resistivities are found for individual blocks, i.e., formations. The resistivities found are: 1000 ohm.m for the sand dunes, 50 ohm.m for the intermediate clayey layer, and 1200 ohm.m for the metamorphic basement. Fig. 4 presents a representative geoelectrical section. The upper layer of relatively high resistivity occurs from a 0- to 25-m depth and can be related to the sand dunes. The intermediate layer of low resistivity lies between the surface and a 50-m depth and is interpreted as colluvium clays. The

Table 2
Physicochemical quality of groundwater along the experimental study

Parameters	Groundwater, Plot I			Groundwater, Plot II			Groundwater, Plot III		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
pH	7.46	7.65	7.90	7.10	7.61	8.00	7.12	7.54	8.10
EC (µS/cm)	1027	1789	3300	1066	1528	4880	1124	2369	3700
COD (mg/L)	31	74	202	10	82	221	8	69	245
TOC (mg/L)	2.52	3.50	4.71	4.29	5.77	7.69	0.44	6.01	10.70
N-NTK (mg/L)	2.26	3.46	4.69	1.70	3.23	4.63	1.70	3.80	9.32
N-NH$_4^+$(mg/L)	0.55	2.37	3.44	0.28	2.26	4.29	0.28	2.40	6.94
N-NO$_3^-$ (mg/L)	3.08	9.62	16.14	0.24	6.30	22.17	0.75	2.63	4.71
Na$^+$ (mg/L)	137	240	346	122	470	786	177	371	594
Ca^{2+} (mg/L)	110	146	218	86	139	235	54	134	252
K$^+$ (mg/L)	14.25	15.50	16.20	14.24	24.35	54.78	6.10	14.61	31.30
Mg^{2+} (mg/L)	35	57	82	33	49	82	17	46	67
PO$_4^{3-}$ (mg/L)	5.90	7.65	13.00	3.24	7.99	14.08	2.00	4.08	6.28

Table 3
Microbiological quality of groundwater along the experimental study

Parameters	Groundwater, Plot I			Groundwater, Plot II			Groundwater, Plot III		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Fecal coliforms (log cfu/100 mL)	0.3	2.5	3.6	0.3	1.9	3.6	0.3	2.4	4.8
Somatic coliphages (log pfu/100 mL)	1.0	1.9	2.7	1.0	1.9	2.8	.6	2.0	3.4
F$^+$-bacteriophages (log pfu/100 mL)	2.0	2.5	3.5	1.0	2.2	3.3	2.2	2.6	3.5

Note: For unrestricted irrigation of edible crops, WHO recommendations indicate a content of FC <3 log cfu/100 mL. There are no indications for groundwater having been recharged. By the time of operation no rules existed in the country for groundwater recharge [14].

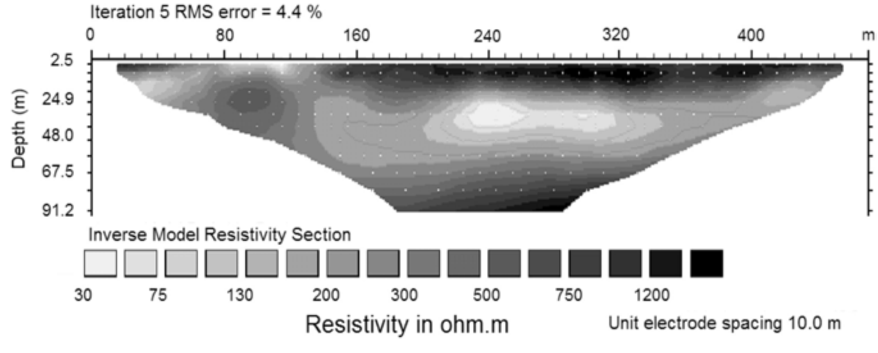

Fig. 4. Geoelectrical cross-section recorded near the Begur wastewater treatment plant showing the thickness and lateral extent of the sand dunes (upper resistive layer), the geometry of the intermediate clay layer and depth of the Paleozoic basement (lower resistive layer).

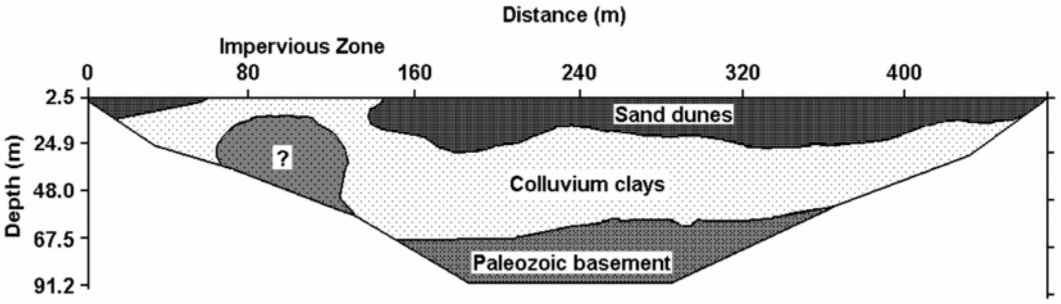

Fig. 5. Geological cross-section derived from the 2-D geoelectrical section showing the geometry of the sand dunes interpreted as the upper resistivity layer. The existence of a low permeability zone in surface is fairly apparent.

lower layer is again a resistive layer related in this case to the Palaeozoic metamorphic basement. Consequently, the cross-sections derived from the inversion process allow discriminating very effectively the subsoil structure, predicting groundwater dynamics and assessing vulnerability risk of the recharge process.

The final characterization of the system shows that there is a small valley with the form of a closed bin, filled with sand, which represents a small aquifer, approximately 3–4 m in depth, with a certain capacity to hold water, which is mainly lost by evapotranspiration, although some percolation to lower layers can be imagined (Fig. 5).

The poplar/soil/subsoil–aquifer system was very effective in removing contaminants from the secondary effluent as indicated in Table 2, and the system was capable of holding an important part of the water coming from the wastewater treatment facility. The rest of the water was disposed of in a different field located 500 m away.

Additional research should be undertaken on the salts accumulated in the system. Nevertheless, the heavy rains typical on the area during autumn will yearly wash the valley quite well.

7. Conclusions

The interaction between reclaimed wastewater, groundwater flow, contaminant transport and water pumping from wells created an awareness of possible problems that may arise for wells, enables preventative measures to be taken and helps solve problems.

When reusing wastewater for aquifer recharge, groundwater protection is difficult, but essential. Due to the large number of threats to groundwater and the vulnerability and value of the resource, it is compulsory to protect groundwater and move our efforts towards aquifer protection. It is also clear that the protection of groundwater requires the development and integration of scientific, technical and regulatory solutions. These considerations relate to questions over how we deal with the characteristics of heterogeneous physical systems such as vadose zone and subsoil geology.

The Begur SPAT is shown to be an adequate system for the management and removal of treated municipal wastewater without soil and groundwater pollution. The infiltration process into the subsoil produces an effective elimination of pathogen microorganisms in groundwater. Sandy soils are in this case an optimal media for the treatment and reuse of reclaimed wastewater.

A non-destructive and spatially integrated multielectrode method for measuring subsoil electrical resistivity was tested in the Begur WWTP. The results provide models of the resistivity structure that can be correlated to the different units of hydrological significance and suggest the potential of electrical imaging for assessing wastewater recharge feasibility. The method was able to infer 2-D delimitation of soil horizons as well aquifer geometry.

Acknowledgements

Thanks are due to SEARSA and Consorci de la Costa Brava for supporting this research project. The fruitful cooperation with colleagues and students from the University of Barcelona is highly appreciated.

References

[1] T. Asano and J.A. Cotruvo, Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. Water Res., 38 (2004) 1941–1951.

[2] A.N. Angelakis, M.H.F. Marecos do Monte, L. Bontoux and T. Asano, The status of wastewater reuse practice in the Mediterranean basin: need for guidelines. Water Res., 33 (1996) 2201–2217.

[3] Standard Methods for the Examination of Water and Wastewater, 19th ed., American Public Health Association, Washington, DC, 1995.

[4] P. Gaspard and J. Schwartzbrod, Determination of parasitic contamination of irrigated vegetables. Water Sci. Technol., 27 (1993) 295–302.

[5] World Health Organization, Health risks in aquifer recharge using reclaimed water — State of the art report, R. Aertgeerts and A. Angelakis, eds., WHO Regional Office for Europe, Copenhagen, 2004.

[6] M. Salgot, M. Folch, J.C. Tapias and A. Torrens, La recarga de acuíferos como herramienta de gestión en la reutilización de aguas residuales: El caso de Begur (Girona), in: El Agua y la Ciudad Sostenible, Serie Hidrologia y Aguas Subterráneas, IGME, 2003, pp. 211–218.

[7] J. Carreras and M. Viladevall, Estudio preliminar del área metamórfica de Sa Riera (Begur, Gerona). Revista d'Investigacions Geològiques, 29 (1974) 67–78.

[8] F.J. Martínez-Gil, Estudio hidrogeológico del Bajo Ampurdán (Gerona). PhD Thesis, University of Barcelona, 1970.

[9] T. Dahlin, 2D resistivity surveying for environmental and engineering applications. First Break, 14 (1996) 275–284.

[10] M.H. Loke, RES2DINV, Ver. 3.50, Rapid 2-D resistivity and IP inversion using the least square method, 2002.

[11] M.H. Loke and R.D. Barker, Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting, 44 (1996) 131–152.

[12] L. Sala, C. Nieto, J.M. Pagès, F. Camps, F. Brissaud, M. Salgot, C. Campos, R. Vieta and J.M. Caus, Eliminación de un efluente secundario mediante un sistema suelo/planta en Begur (Costa Brava, Girona, España), in: Utilización de Aguas Residuales Regeneradas y Biosólidos, Water Environment Federation/Adecagua, Marbella, Spain, 1997, pp. 7–31.

[13] C. Campos, Indicadores de contaminación fecal en la reutilización de agua residual regenerada en suelos. PhD Thesis, University of Barcelona, 1999.

[14] World Health Organization, Health guidelines for the use of wastewater in agriculture and aquaculture WHO Technical Report, Series 778, Geneva, 1989.