Cost of reclaimed municipal wastewater for applications in seasonally stressed semi-arid regions

E. Gonzalez-Serrano, J. Rodriguez-Mirasol, T. Cordero, A. D. Koussis and J. J. Rodriguez

ABSTRACT

The effectiveness and the cost of wastewater treatment options appropriate for different uses of reclaimed water in seasonally stressed regions are evaluated. Data are for applications in locales of the semi-arid regions of the Mediterranean rim and islands. These regions experience water demand stresses mainly from seasonally intense tourism and agriculture. With precipitation-derived resources fixed, recycled treated wastewater is a non-traditional, potentially cost-effective alternative water source that can be secured to meet certain demands. Different levels of wastewater treatment have been studied, T_i, satisfying effluent quality standards corresponding to four final effluent destinations: T_1, for a sea outfall or surface waters (zero-alternative, for comparison); T_2, for irrigation (USEPA guidelines); T_3, for aquifer recharge by infiltration from spreading fields (guidelines of the California Department of Health Services) and T_4, for aquifer recharge by direct injection (USA Drinking Water Standards). The result is a set of cost functions for investment *I* and for operation and maintenance *O&M* developed based on the technical design and the cost estimation of the unit processes and operations of the studied wastewater treatment plant (WWTP).

Key words | cost function, reclaimed water, wastewater treatment

E. Gonzalez-Serrano
J. Rodriguez-Mirasol (corresponding author)
T. Cordero
Department of Chemical Engineering,
School of Industrial Engineering,
University of Málaga,
Campus de El Ejido, s/n,
29013 Málaga,
Spain
E-mail: *mirasol@uma.es*

A. D. Koussis
Institute for Environmental Research and Sustainable Development,
National Observatory of Athens,
I. Metaxa & Vassileos Pavlou,
GR 152 36 Palaia
Penteli, Athens,
Greece

J. J. Rodriguez
Department of Chemical Engineering,
University Autónoma of Madrid,
Cantoblanco, 28049 Madrid,
Spain

INTRODUCTION

It is estimated that, over the past three centuries, water withdrawals have risen by a factor of 35 while the world population has increased eightfold. The increased pressures on water resources thus result from the expectations of a growing population for a higher standard of living, especially in developing countries. These pressures are often most severe in coastal zones, where population densities are typically high and economic activities intense; of course, the prevailing climatic, geologic, soil and hydrologic conditions differentiate the water resources problems. In Europe, water shortages have intensified in its southern regions, especially in the Mediterranean rim and islands. The causes can be found in the cumulative effects of population growth, expanding economy and higher standards of living that demand increased water supply, coupled with limited or depleted water resources of deteriorating quality.

Water stresses occur not only during drought cycles, but also regularly where tourism is strong. Tourists visit Mediterranean locales preferentially in the summer, often causing a many-fold population increase, and consume about twice the water of a local consumer. In addition, the mild temperatures and good soils of the Mediterranean region have led to intense irrigated agriculture, with peak water demand in the dry period May–September (~ 10% of mean annual rainfall). For example, water demand is markedly seasonal in the southern Aegean islands of Greece, in Andalusia and Costa del Sol in Spain, in Cyprus and along the coast of Israel, where agriculture and tourism are prominent economic activities. Island resources are stressed even more, as the geographic isolation precludes such traditional options as inter-basin water transfer, except via expensive tank ships (Koussis *et al.* 2002).

With precipitation-derived resources fixed, alternative sources of water must be secured to meet the demand. Two non-traditional, potentially cost-effective water sources are readily identified (World Bank 1995): (i) saltwater that can be treated to potable quality standards and (ii) treated wastewater that can be recycled to meet certain demands. These sources can be combined in a scheme for the management of a coastal region's water resources, on the premise that intensely exploited aquifers inevitably suffer sea intrusion, as not all withdrawn water is returned and extractions periodically exceed recharge. The potential of wastewater re-use for the enhancement of the hydrologic budget and the protection of aquifers from seawater intrusion has been long recognized (e.g. Water Pollution Control Federation 1989) and artificial recharge for the creation of a hydraulic barrier to the advance of the saltwater front is practised widely. For example, in the Netherlands the recharge is with treated surface water, in Israel with treated wastewater and in Cyprus and in California with a mix of freshwater and treated wastewater (Koussis *et al.* 2002). Desalting of brackish waters (waters of slight salinity, 1,000–3,000 ppm total dissolved solids (TDS), to moderate salinity, 3,000–10,000 ppm TDS; McCutcheon *et al.* 1993) requires about half the energy for seawater desalination and has favourable economics (Georgopoulou *et al.* 2001) (important in islands not connected to the power grid).

These circumstances open up an opportunity for sustainable management of the stressed resources of coastal aquifers: enhancing the hydrologic balance through aquifer recharge with treated wastewater, to curtail seawater intrusion thus reducing the cost of any groundwater desalination. To facilitate assessment of the management options, the Decision Aid Tool (DAT), outlined in Figure 1, was developed in the project WASSER, Utilisation of Groundwater Desalination and Wastewater Reuse in the *Wa*ter *S*upply of *Se*asonally-Stressed *R*egions (Koussis 2001). Alternatives are evaluated objectively through modelling encompassing the physics, engineering and economics of the natural and engineered subsystems. The natural subsystem consists of the watershed and the aquifer; the engineered subsystem includes desalination, wastewater treatment and pumping and storage facilities. The DAT shell

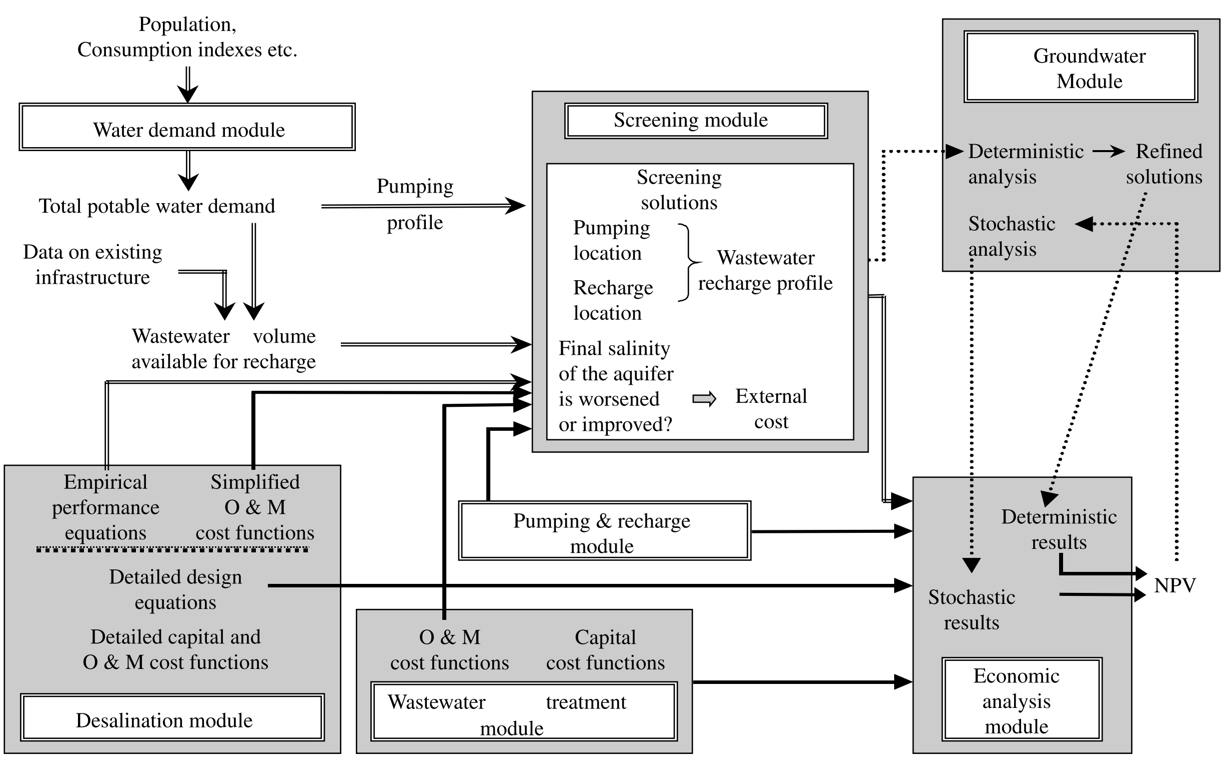

Figure 1 | Optimisation procedure used in WASSER: screening and final design stages.

contains an optimisation application for screening alternative recharge/extraction scenarios and a package for evaluating in-depth the most promising scenarios, based on economics and environmental criteria.

Here, we report on the wastewater treatment and re-use aspects of WASSER. The effectiveness and the cost of various wastewater treatment unit processes and operations that are appropriate for different uses of reclaimed water in seasonally stressed regions are evaluated. Data are for applications in locales of the Mediterranean rim and islands.

BACKGROUND INFORMATION

Groundwater exceeds 60% of the global water suitable for human consumption and thus represents an important source of drinking water in many regions of the world (Bachmat 1994); groundwater is the prime water source in semi-arid regions. These are regions characterized by values of the UNESCO moisture index $I_h = \mathrm{P/PET} \leq 0.5$, where $P =$ annual precipitation, $PET =$ potential evapotranspiration, indicating potential atmospheric losses far in excess of precipitation (e.g., $PET > 3P$ in Athens, Greece; Koutsoyiannis & Baloutsos 2000). In semi-arid regions, precipitation is low and greatly variable and actual evapotranspiration high; hence there are extended periods of no runoff (ephemeral streamflow) and no recharge, as for example in Southern California. Cyprus, southeast Greece, southeast Italy plus Sicily, Malta, south Portugal, southeast and parts of Central Spain and the Canary and Balearic Islands are semi-arid regions of the European Union; other Mediterranean semi-arid regions are in the Middle East and North Africa (Koussis *et al.* 2002).

Sea intrusion is a serious threat to coastal aquifers that causes a, largely, human-induced groundwater contamination by a natural chemical; this can be extensive or localised, depending on pumping rate and location of wells (Ergil 2000). The threat of seawater intrusion is more acute in semi-arid regions where overdrafts are more likely to be used in handling periodic water shortages. Mixing freshwater with 2% of seawater (salinity ~ 35,000 ppm TDS) raises water salinity sufficiently to make it unsuitable for drinking (potable water standard is 500 ppm TDS), 5% mixing makes freshwater unsuitable for irrigation (Custodio and Bruggeman 1987), excluding salt-resistant plants.

Re-use of treated wastewater is practised in various parts of the world, but under non-uniform standards; for example, European standards do not exist and as a result different regions use their own rules (Salgot and Pascual 1996). The two most widely used standards are those of the World Health Organisation (WHO) and of the State of California, USA (Title 22). The less stringent WHO standard can be met with simpler technologies; the intent is to replace the use of raw wastewater for irrigation in regions with inadequate technologies of water supply and sanitation and thus inhibit the spread of waterborne diseases. The California standard aims to ensure that reclaimed water is nearly free of pathogens, acceptable by a health-conscious public (number of US-regulated drinking water contaminants: 25 in 1980, over 150 in 2000; WEF and AWWA 1998). Thus, the use of reclaimed wastewater for purposes such as irrigation, golf course watering (important in tourist areas such as the Canary Islands and Costa del Sol), or aquifer recharge unavoidably requires tertiary or advanced wastewater treatment (Water Environment Federation 1992; Kanarek and Michail 1996; Haruvy 1997; Broens *et al.* 2004; Pollice *et al.* 2004).

The specification of an appropriate wastewater treatment plant (WWTP) demands considerations beyond process decision and design criteria. The treatment processes to be chosen for the desired application depend on several factors: flow rate, waste strength and toxicity, availability of land, climatic conditions, degree of permanence desired, costs and discharge standards. The water recharge method will also influence, decisively, the treatment requirements. Given that the economics determines largely the strategy for combating environmental contamination, a complete study of a wastewater treatment problem requires the economic analysis of the processes and systems. Therefore cost functions have been developed based on the technical design and the cost estimation of the unit processes and operations of the studied WWTP.

METHODOLOGY

Composition and sources of wastewater

Raw wastewater composition constitutes an important factor in the WWTP design. Municipal wastewater is the most widely available source of re-usable water, which is estimated to increase in the future. The characteristics of domestic wastewater are rather reproducible and predictable in almost all cases. The waste reflects the character and practices of the population served and, typically, the flow variations follow daily and weekly lifestyle patterns of the serviced residential customers. Residential use of water typically adds dissolved inorganic solids, nitrogen, phosphorus and, especially, both dissolved and suspended organic material, important parameters that impact on the viability of using domestic wastewater as a re-use source.

Water discharges after agricultural use, although estimated to decrease in the future, create significant opportunities for water conservation and wastewater re-use, especially where agriculture is a prime element of a region's economy and uses a large fraction of the supplied water. It is estimated that almost half of the irrigation water becomes return flow. However, the returned water becomes highly mineralized and, generally, unfit for direct re-use in irrigation, as it would cause salt build-up on the land, sharply reducing productivity. Several agricultural uses, especially those coupled with raising livestock, also increase the bacterial levels of the agricultural discharges that pose a threat to human health. In addition, accumulation of pesticides and of fertilizers, high levels of nitrogen and phosphorus especially, limit the direct use of agricultural return flows for aquifer recharge (Water Pollution Control Federation 1989; Lee 1990). Other potential sources of re-usable wastewater are industrial effluents; however industries usually have their own purification systems and efficient water recycling is expected to increase substantially in the future.

As mentioned above, this work focuses on regions suffering seasonal water stress such as those located in the Mediterranean basin: for example, the Aegean Islands, Cyprus, Costa del Sol and Israel, or in the Canary Islands. The economy of these regions relies heavily on tourism; agriculture is solid and the presence of industry small. Municipal wastewater has been thus considered as the raw wastewater source for the design of WWTPs. The composition of this wastewater tends to be fairly uniform, given its predominant origin and the similarity of social, economic, terrain and climate conditions among the regions.

Daily per capita values of domestic load contribution of at least 0.08 kg of five-day biochemical oxygen demand (BOD_5), 0.09 kg of suspended solids (SS) and average daily flow volume of 350 to 400 l per capita are recommended for the design of new WWTPs (Water Environment Federation 1991). However, the values of these parameters considered in this work for the design of the plants are based on data obtained from different wastewater compositions of seasonally stressed regions of the Mediterranean basin (Koussis 2001). Table 1 presents the main characteristics of the raw wastewater used in this work. These parameters are typical of a municipal wastewater considered as strong (Metcalf and Eddy 1991), with high BOD_5, chemical oxygen demand (COD) and SS

Table 1 | Main characteristics of the raw wastewater used in this study

Constituent	Concentration (mg l^{-1})*
Total suspended solids (TSS)	380
Total dissolved solids (TDS)	950
Five-day biochemical oxygen demand BOD_5)	425
Chemical oxygen demand (COD)	1,020
Total Kjeldahl nitrogen (TKN)	39.9
Organic nitrogen (N_{org})	65
Ammonia-N (NH_4^+-N)	23.4
Nitrate-N	<1
Nitrite-N	<1
Total nitrogen content-N	63.3
Total phosphorus-P	15
Chloride	297
Chromium	1–3
Boron	0.60
Total coliforms (units 100 ml^{-1} of wastewater)	10^8
Fecal coliforms (units 100 ml^{-1} of wastewater)	10^7

* Except total and fecal coliforms

loading contributions, characteristic of semi-arid areas with wide seasonal population fluctuations.

Evaluation of wastewater flow rate

The design of most processes of municipal WWTPs is based, mainly, on the flow rate of the wastewater to be treated. Flow rates can be obtained experimentally or can be estimated. The average daily flow rate is, usually, calculated from the equivalent population and the per capita consumption. Information is also needed on the daily peak flow, because the design of some unit operations is based on this parameter. The daily peak flow can be estimated as a function of the average daily flow rate (Water Environmental Federation 1991). Taking into account that the transient population in Southern European tourist areas is, normally, spread among small to medium-size towns along the coast, five equivalent populations have been considered, ranging from 12,000 to 208,000 persons. A water consumption of 300 l per capita per day has been estimated, based on data available from various tourist regions (Koussis 2001). Table 2 shows the equivalent populations and daily and peak wastewater flow rates used in this study.

Applications of wastewater re-use and water quality requirements

The level of treatment that a given wastewater requires for a target application is an essential determinant of the best available and cost-effective treatment technology. This treatment level depends on the characteristics of the influent wastewater and on the required effluent water quality. The applications of the reclaimed municipal wastewater considered are irrigation and aquifer recharge. In the case of irrigation, the required wastewater treatment level depends on the cultivated crops. The concentration limits for the WWTP effluent constituents vary according to the crop and the potential for public contact. Health considerations are less strict for irrigation of non-food crops or for land irrigated by overland flow in isolated areas with no public access, than for food crops or irrigation in areas of public access such as yards, parks and golf courses. This study has considered irrigation of food crops and public areas as wastewater re-use applications.

Surface spreading, streambed infiltration and direct injection are methods of aquifer recharge with reclaimed water. Of these methods, direct injection is especially effective in creating freshwater barriers in coastal aquifers against seawater intrusion. The quality standards of reclaimed water for aquifer recharge are based on the condition of non-degradation of existing groundwater supplies. This is particularly important for direct injection systems, since the injected wastewater does not benefit from additional treatment in the aeration zone, as happens in other recharge methods. We have studied aquifer recharge by direct injection and by surface spreading as wastewater re-use target applications in which groundwater is considered a source of potable water.

Table 2 | Equivalent population and daily and peak wastewater flow rates

Equivalent population (inhabitants)	Daily wastewater flow rate ($m^3\ day^{-1}$)	Peak wastewater flow rate ($m^3\ h^{-1}$)
12,000	3,600	360
32,000	9,600	960
64,000	19,200	1,920
96,000	28,800	2,880
208,000	62,400	6,240

Economic considerations

Factors that influence the investment cost of WWTPs include plant capacity, design criteria, treatment process, land cost, location of construction and weather conditions, as well as competition among bidders and suppliers and stability of the local and national economic conditions (Montgomery 1985). Data of built WWTPs are a useful guide for cost-adjustments to account for the different conditions that apply to the projects of interest. Investment and operation and maintenance costs have been estimated for different WWTPs and their unit operations, based on data obtained from reports on WWTPs installed in Spain (the use of Spanish data is incidental; the methodology is generally applicable). Investment and operation and maintenance costs have been estimated as

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functions of the wastewater flow rate to be treated and of the required level of treatment, for the year 2004.

The investment cost (I) includes the following:

1. Total construction cost (53% of I)
   - 1.1. Civil work costs (54% of item 1. or 28.6% of I)
     - 1.1.1. Construction costs of specific water treatment components (75.3% of item 1.1 or 21.5% of I)
     - 1.1.2. Operation buildings (14.1% of item 1.1 or 4.0% of I)
     - 1.1.3. Plant piping (10.6% of item 1.1 or 3.1% of I)
   - 1.2. Electro-mechanical work costs (46% of item 1. or 24.4% of I)
     - 1.2.1. Machinery and apparatus (71% of item 1.2 or 17.3% of I)
     - 1.2.2. Electrical installation (29% of item 1.2 or 7.1% of I)
2. Contingencies (20.0% of item 1 or 10.6% of I)
3. Overhead expenses (17.0% of item 1 or 9% of I)
4. Engineering (21.1% of item 1 or 11.2% of I)
5. Industrial profit (7.2% of item 1 or 3.8% of I)
6. Value-added tax (VAT) (23.4% of item 1 or 12.4% of I)

Engineering includes engineering and contractor costs. Overhead expenses involve such items as cost for maintaining office space, for administrative personnel and for securing insurance, permits, etc. Costs of land and of special site preparation have

Table 3 | Water quality requirements of reclaimed wastewater for final re-use destination

Constituent	Surface water [mg l^{-1}]* (91/271/EEC)	Irrigation [mg l^{-1}]* (EPA Guidelines)	Aquifer recharge by infiltration [mg l^{-1}]* (California DoHS)	Aquifer recharge by direct injection [mg l^{-1}]* (US Drinking Water Standard)
Total suspended solids (TSS)	35		15	0
Total dissolved solids (TDS)		450	700	500
5-day biochemical oxygen demand (BOD_5)	25			0
Chemical oxygen demand (COD)	125			
Total nitrogen – N	10**	5		
Kjeldahl nitrogen				1
Ammonium				0.5
Nitrate – N				10
Nitrate – N + Nitrite – N			10	10
Total phosphorus – P	1**			<1
Chloride		100	250	200
Coliform [units 100 ml^{-1}]		2.2	2.2	0
Total bacteria [units 100 ml^{-1}]				0
Residual chlorine		1		

*Except coliform and total bacteria
**Condition when receiving surface water is susceptible to eutrophication

not been considered because they are highly variable. Construction cost of specific water treatment components includes cost of excavation and site work for the individual unit operations, equipment, concrete and steel, and labour.

The main costs associated with the operation and maintenance of wastewater treatment plants include, in general, labour, materials, chemicals, repairs and energy for both processes and enclosures. For this study the operation and maintenance costs have been itemized as follows:

1 Annual fixed costs: Personnel and maintenance
2 Annual variable costs
 2.1 Chemicals
 2.2 Energy
3 Amortization: an amortized capital at 4% in 20 years has been taken into account.

Personnel and maintenance costs have been estimated at an average rate of €25 per man-hour. The electricity rates used are those of the Spanish Ministry of Industry (B.O.E. 313 (R.D. 1436/ 2002), 27 December 2002): energy rate = €0.04 kWh^{-1}.

RESULTS AND DISCUSSION

The design of WWTPs depends, obviously, on the final effluent quality prescribed by law, which varies depending on the discharge destination. When available, European Union (EU) legislation has been considered in this work. However, USA regulations and guidelines have been taken into account, either when there is a lack of EU law or regulation, or when EU standards are less demanding than the USA standards. Levels of wastewater treatment, T_i, satisfying effluent quality standards corresponding to four final effluent destinations have been studied: T_1, for a sea outfall or surface waters; T_2, for irrigation (USEPA guidelines); T_3, for aquifer recharge by infiltration from spreading fields (guidelines of the California Department of Health Services); and T_4, for aquifer recharge by direct injection (USA Drinking Water Standards). Treatment for sea discharge (T_1) has been included as a baseline option for purposes of comparison (zero-alternative). Table 3 presents the water quality standards for the effluent destinations studied in this work, according to the more restrictive existing legislation.

Pre-treatment, conventional primary and secondary treatment and disinfection have been considered in this study as the minimum treatment required when the final effluent destination is the sea or surface waters, provided there is no danger of eutrophication. The discharge levels of municipal effluents according to EU Directive 91/271/EEC

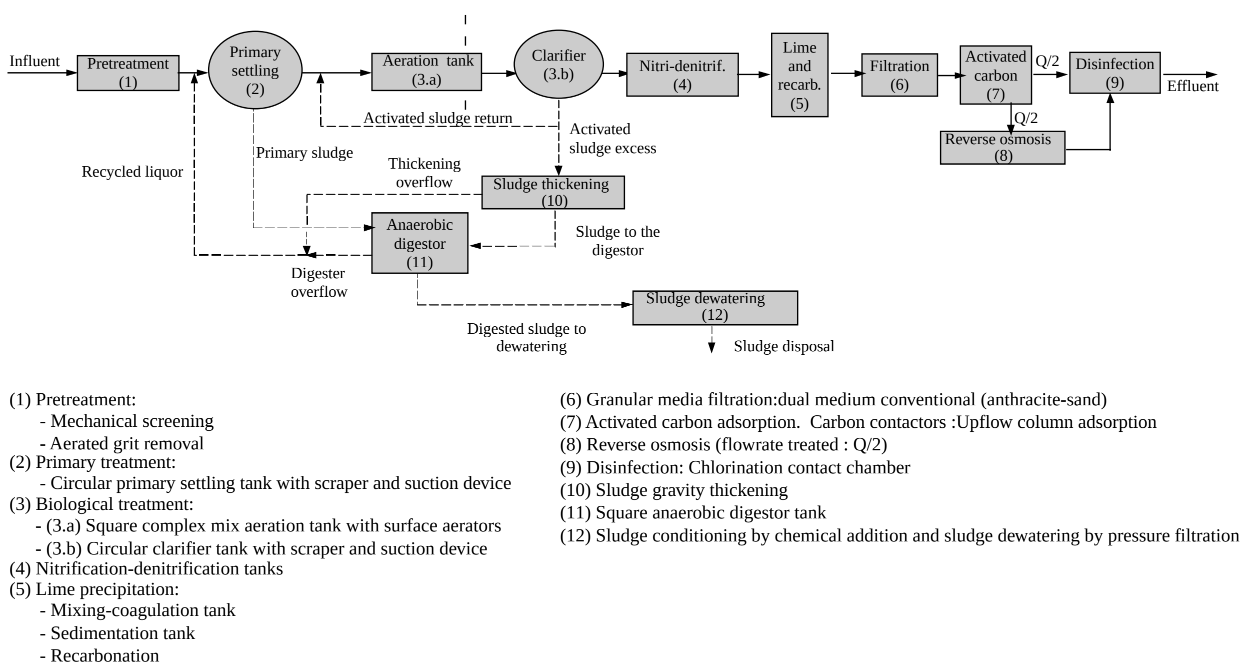

Figure 2 | Flow diagram for the T_4 – WWTP.

Table 4 | Breakdown of the investment cost for T_1 – WWTP

Investment cost (€) for	WW flow rate ($m^3\ h^{-1}$): 150	400	800	1,200	2,600
1. Total construction costs:	837,200	1,925,700	3,044,500	4,162,400	7,004,200
1.1. Costs of civil work:	451,800	1,039,200	1,642,900	2,246,100	3,779,600
1.1.1. Construction costs of specific water treatment components	339,600	781,200	1,235,100	1,688,500	2,841,300
1.1.2. Operation buildings	63,200	145,300	229,800	314,100	528,600
1.1.3. Plant piping	49,000	112,600	178,100	243,500	409,700
1.2. Costs of electromechanical works:	385,500	886,600	1,401,700	1,916,300	3,224,600
1.2.1. Machinery and apparatus	273,300	628,600	993,800	1,358,700	2,286,300
1.2.2. Electrical installation	112,200	258,000	407,900	557,600	938,300
2. Contingencies	167,400	385,100	608,900	832,500	1,400,900
3. Overhead	142,200	327,000	517,000	706,800	1,189,400
4. Engineering	177,000	406,900	643,400	879,600	1,480,100
5. Industrial profit	60,000	138,100	218,300	298,400	502,200
6. Value-added tax (VAT)	195,900	450,600	712,400	973,900	1,638,700
Total investment costs	**1,579,700**	**3,633,400**	**5,744,500**	**7,853,600**	**13,215,500**

(1991) have been taken into account in this case. The pre-treatment includes mechanical screening and aerated grit removal. The primary treatment consists of circular settling tanks with scraper and suction devices, the biological treatment incorporates complex mix aeration tanks with surface aerators and circular secondary settling tanks, and a chlorination contact chamber constitutes the disinfection unit. If the quality of the receiving water body is susceptible to degradation by nitrogen and phosphorus inputs, an integrated process for nutrient control (nitrification–denitrification, lime precipitation) should be designed to meet nutrient limitations in the effluent stream.

Water quality requirements for irrigation vary, depending on the crop and on the potential for public contact. As stated in the Methodology, this study contemplates irrigation of food crops and public areas such as parks and golf courses. In this case, the concentration limits for the constituents of re-used wastewater are those imposed by the USEPA guidelines given in Table 3. The minimum treatment required for achieving this water quality (T_2) would be that of a T_1-WWTP, plus two more advanced treatments, nitrification–denitrification and filtration.

Surface recharge techniques are among the simplest and most widely applied methods for replenishment of groundwater. Surface spreading is most effective where no layers occur between the land surface and aquifer impeding infiltration. It has relatively low construction costs and is easy to operate and maintain. Field studies of spreading techniques have shown that, of the many factors governing the amount of water entering the aquifer, the area of recharge and the length of time that the water is in contact with the soil are considered to be the most important. When

Table 5 | Breakdown of the investment cost for T_2 – WWTP

Investment cost (€) for	WW flow rate (m^3 h^{-1}): 150	400	800	1,200	2,600
1. Total construction costs:	1,544,900	2,915,000	4,664,000	5,830,000	9,619,500
1.1. Costs of civil work:	833,700	1,573,000	2,516,800	3,146,000	5,190,900
1.1.1. Construction costs of specific water treatment components	626,700	1,182,500	1,892,000	2,365,000	3,902,200
1.1.2. Operation buildings	116,600	220,000	352,000	440,000	726,000
1.1.3. Plant piping	90,400	170,500	272,800	341,000	562,600
1.2. Electromechanical work costs:	711,300	1,342,000	2,147,200	2,684,000	4,428,600
1.2.1. Machinery and apparatus	504,300	951,500	1,522,400	1,903,000	3,140,000
1.2.2. Electrical installation	207,000	390,500	624,800	781,000	1,288,600
2. Contingencies	309,000	583,000	932,800	1,166,000	1,923,900
3. Overhead	262,300	495,000	792,000	990,000	1,633,500
4. Engineering	326,500	616,000	985,600	1,232,000	2,032,800
5. Industrial profit	110,800	209,000	334,400	418,000	689,700
6. Value-added tax(VAT)	361,500	682,000	1,091,200	1,364,000	2,250,600
Total investment costs	**2,915,000**	**5,500,000**	**8,800,000**	**11,000,000**	**18,150,000**

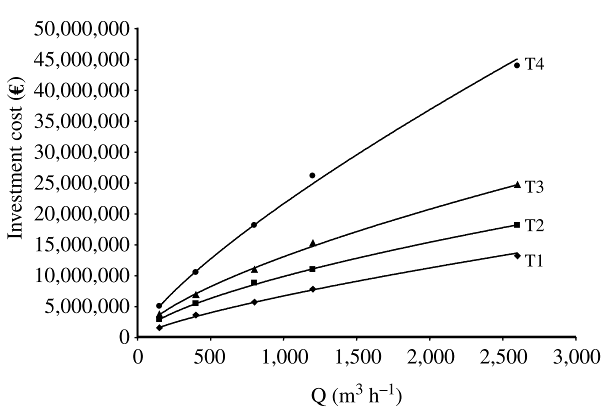

Figure 3 | Investment cost as a function of wastewater flow rate for the different WWTPs studied.

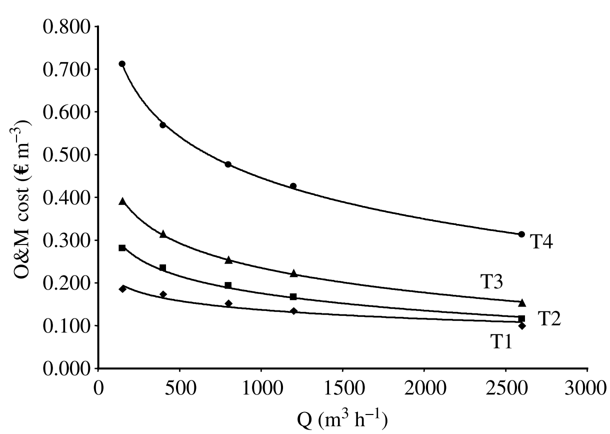

Figure 4 | O&M cost as a function of wastewater flow rate for the different WWTPs studied.

Table 6 | Breakdown of the investment cost for T_3 – WWTP

	WW flow rate ($m^3\ h^{-1}$)				
Investment cost (€) for	**150**	**400**	**800**	**1,200**	**2,600**
1. Total construction costs:	1,999,700	3,672,900	5,830,000	8,103,700	13,117,500
1.1. Costs of civil work:	1,079,100	1,982,000	3,146,000	4,373,000	7,078,500
1.1.1. Construction costs of specific water treatment components	811,200	1,489,900	2,365,000	3,287,300	5,321,200
1.1.2. Operation buildings	150,900	277,200	440,000	611,600	990,000
1.1.3. Plant piping	117,000	214,800	341,000	474,000	767,200
1.2. Electromechanical work costs:	920,600	1,690,900	2,684,000	3,730,800	6,039,000
1.2.1. Machinery and apparatus	652,700	1,198,900	1,903,000	2,645,200	4,281,700
1.2.2. Electrical installation	267,900	492,000	781,000	1,085,600	1,757,200
2. Contingencies	399,900	734,600	1,166,000	1,620,700	2,623,500
3. Overhead	339,600	623,700	990,000	1,376,100	2,227,500
4. Engineering	422,600	776,200	1,232,000	1,712,500	2,772,000
5. Industrial profit	143,400	263,300	418,000	581,000	940,500
6. Value-added tax (VAT)	467,800	859,300	1,364,000	1,896,000	3,069,000
Total investment costs	**3,773,000**	**6,930,000**	**11,000,000**	**15,290,000**	**24,750,000**

direct discharge is practised, the amount of water entering the aquifer depends on three factors: the infiltration rate, the percolation rate and the capacity for horizontal water movement; in a homogeneous aquifer, the infiltration rate is equal to the percolation rate.

A common problem of recharge by surface spreading is clogging of the surface material, which reduces the infiltration capacity. Clogging results from silting, chemical precipitation and accumulation of organic matter, therefore periodic maintenance is essential, consisting of scraping the infiltration surface to remove accumulated silt and organic matter. In the case of injection wells, periodic maintenance of the system consists of pumping and flushing with a mildly acidic solution to remove encrusting chemical precipitates and bacterial growths on the well tube slots.

Information regarding the cost of artificial recharge of aquifers is relatively scarce. The cost of recharge systems depends, in general, upon the degree of treatment of the source water, the distance over which it must be transported, and the stability of the recharge structures and their resistance to silting and clogging (Asano 1985; Botzan *et al.* 1999; Donovan *et al.* 2002; Asano and Cotruvo 2004). Initial and operation costs for artificial recharge by spreading channels and grounds, by percolation tanks, and by injection wells have been reported by Rushton and Phadtare (1989). Pilot projects of artificial recharge were carried out in the Mehsana area of Gujarat, India, in both alluvial and limestone aquifers; but these data should be treated carefully, because land price and labour and energy costs are not available. This information would be interesting only for comparing the various treatments used.

Table 7 | Breakdown of the investment cost for T_4 – WWTP

	WW flow rate (m^3 h^{-1})				
Investment cost (€) for	**150**	**400**	**800**	**1,200**	**2,600**
1. Total construction costs:	2,681,800	5,596,800	9,619,500	13,875,400	23,320,000
1.1. Costs of civil work:	1,447,200	3,020,200	5,190,900	7,487,500	12,584,000
1.1.1. Construction costs of specific water treatment components	1,087,900	2,270,400	3,902,300	5,628,700	9,460,000
1.1.2. Operation buildings	202,400	422,400	726,000	1,047,200	1,760,000
1.1.3. Plant piping	156,900	327,400	562,600	811,600	1,364,000
1.2. Electromechanical work costs:	1,234,600	2,576,700	4,428,600	6,387,900	10,736,000
1.2.1. Machinery and apparatus	875,400	1,826,900	3,139,900	4,529,100	7,612,000
1.2.2. Electrical installation	359,200	749,800	1,288,600	1,858,800	3,124,000
2. Contingencies	536,400	1,119,400	1,923,900	2,775,100	4,664,000
3. Overhead	455,400	950,400	1,633,500	2,356,200	3,960,000
4. Engineering	566,700	1,182,700	2,032,800	2,932,200	4,928,000
5. Industrial profit	192,300	401,300	689,700	994,800	1,672,000
6. Value-added tax (VAT)	627,400	1,309,400	2,250,600	3,246,300	5,456,000
Total investment costs	**5,060,000**	**10,560,000**	**18,150,000**	**26,180,000**	**44,000,000**

Injection wells in hard rock areas, which tend to be shallower and have a lesser risk of clogging, seem to be less expensive. Percolation tanks appear to be least expensive in terms of initial construction costs; however, this seems to be true in areas where the tanks already exist. In such cases, the initial cost only involves the cleaning of the bed of the tank.

No uniform European regulations exist for aquifer recharge with reclaimed wastewater. There is wide agreement that the WHO guidelines are insufficient, but so far, there is no general consensus on the best approach to follow. Most of the available data are for the standards of the California Department of Health Services (CalDoHS), which seem to have become established in several parts of the world. In 1976, the CalDoHS developed criteria for aquifer recharge with reclaimed water by surface spreading. Reclaimed water quality limits were specified for inorganic chemicals, pesticides, COD, total organic carbon (TOC) and radioactivity. The treatment specified in the draft regulations was conventional secondary treatment, followed by carbon adsorption (or dual-media filtration) and percolation through at least 3 m of unsaturated soil. Maximum application of reclaimed water was restricted to not more than 50% of the total water spread during a 12-month period. The draft regulations also specified a minimum residence time of one year in the underground before groundwater withdrawal. Other proposed requirements included detailed reports on hydrogeology and spreading operations, establishment of a programme to control industrial sources, development of contingency plans and implementation of a programme to monitor the health of the population receiving reclaimed water.

Table 8 | Breakdown of the O&M cost for T_1 – WWTP

	Annual fixed costs (€ year^{-1})	Annual variable costs (€ year^{-1})			
WW flow rate (m^3 h^{-1})	Personnel & maintenance	Chemicals	Energy	Amortization (€ year^{-1})	O&M (€ m^{-3})
150	88,200	18,400	73,400	63,200	0.185
400	104,400	64,300	292,700	145,300	0.173
800	121,000	114,100	598,800	229,800	0.152
1,200	137,600	134,500	825,900	314,100	0.134
2,600	179,800	189,800	1,359,700	528,600	0.099

Table 9 | Breakdown of the O&M cost for T_2 – WWTP

	Annual fixed costs (€ year^{-1})	Annual variable costs (€ year^{-1})			
WW flow rate (m^3 h^{-1})	Personnel & maintenance	Chemicals	Energy	Amortization (€ year^{-1})	O&M (€ m^{-3})
150	98,500	30,700	122,800	116,600	0.281
400	124,600	85,800	390,600	220,000	0.234
800	154,100	135,200	709,600	352,000	0.193
1,200	183,000	157,800	969,000	440,000	0.166
2,600	255,800	197,700	1,449,300	726,000	0.115

Table 10 | Breakdown of the O&M cost for T_3 – WWTP

	Annual fixed costs (€ year^{-1})	Annual variable costs (€ year^{-1})			
WW flow rate (m^3 h^{-1})	Personnel & maintenance	Chemicals	Energy	Amortization (€ year^{-1})	O&M (€ m^{-3})
150	105,500	51,500	206,000	150,900	0.391
400	137,500	123,400	561,800	277,200	0.314
800	174,900	186,100	976,900	440,000	0.254
1,200	211,100	212,400	1,304,200	611,600	0.223
2,600	301,800	263,700	1,933,600	990,000	0.153

Table 11 | Breakdown of the O&M cost for T_4 – WWTP

	Annual fixed costs (€ year^{-1})	Annual variable costs (€ year^{-1})			
WW flow rate (m^3 h^{-1})	**Personnel & maintenance**	**Chemicals**	**Energy**	**Amortization (€ year^{-1})**	**O&M (€ m^{-3})**
150	115,400	123,400	493,600	202,400	0.711
400	156,500	253,900	1,156,400	422,400	0.568
800	206,200	384,600	2,019,100	726,000	0.476
1,200	253,400	444,000	2,727,400	1,047,200	0.425
2,600	371,600	597,700	4,382,900	1,760,000	0.312

In 1978, the CalDoHS revised the Wastewater Reclamation Criteria to require that reclaimed water for recharge by surface spreading of aquifers used for domestic water supply be of a quality that fully protects public health. Several factors were considered, such as treatment provided, effluent quality and quantity, spreading-area operations, soil characteristics, hydrogeology, residence time and distance to locations of withdrawal. In July 1992, draft State regulations were promulgated in California governing the use of reclaimed water for recharge of potable-water aquifers, whether through wells or surface recharge facilities, which are very similar to those already mentioned. Under the draft regulations, all recharge waters would have to undergo biological oxidation and disinfection, with well injection also requiring filtration and organic removal.

In this study we have used the CalDoHS water quality requirements for aquifer recharge by surface spreading and the US Drinking Water Standards (US National Primary and Secondary Drinking Water Regulation) for recharge by direct injection. Under these considerations, the T_3 – WWTP required for aquifer recharge by infiltration consists of a T_2 – WWTP, plus an activated carbon adsorption system with upflow columns as carbon contactors. The design of the T_4 – WWTP required for aquifer recharge by direct injection is, basically, that for a T_3 – WWTP, plus a lime precipitation and re-carbonation process, including mixing-coagulation and sedimentation tanks and a reverse osmosis system. Figure 2 shows the flow diagram for the T_4 – WWTP, which contains the unit processes and operations considered for each of the four WWTPs.

Extended aeration has been considered as secondary treatment for plants with wastewater flow rate less than 5,000 m^3 day^{-1}. In this case, a first step of pre-thickening by gravity thickening is followed by aerobic digestion, involving oxidation of cellular organic matter through synthesis and endogenous metabolism. A final step of sludge conditioning by chemical addition and sludge dewatering by filter press has been used for the sludge treatment, given that only a small amount of sludge is produced. Primary sedimentation is not used for this design. With regard to the larger plants, with flow rate higher than 5,000 m^3 day^{-1}, activated sludge has been considered as secondary treatment. As a considerable amount of sludge is produced in this case, the sludge treatment line consists of a first step of thickening by gravity thickening, to provide a concentrate sludge underflow, followed by an anaerobic digester where the solid organic materials are stabilized by hydrolysis, which in turn are broken down to volatile fatty acids that are subsequently converted to methane and carbon dioxide by methane-forming bacteria. A final process of sludge conditioning by

Table 12 | Fitting parameters obtained for I and O&M cost functions

WW treatment	A	n	r^2 (I)	α	β	r^2 (O&M)
T1	40,363	0.741	0.997	−0.030	0.346	0.932
T2	118,331	0.641	0.999	−0.058	0.577	0.994
T3	131,559	0.666	0.999	−0.083	0.811	0.999
T4	108,173	0.767	0.999	−0.137	1.404	0.999

chemical addition (poly-electrolytes) and sludge dewatering is to be used before disposing of the sludge cake.

Reverse osmosis, which is effective in reducing turbidity and in removing a high percentage of bacteria and viruses, inorganic salts and organic material from pre-treated municipal wastewater, has been considered for the case of recharge by direct injection. However, only half of the wastewater flow rate is to be treated by reverse osmosis, which is sufficient for reaching the required level of treatment (Water Pollution Control Federation 1989). This way of operating the plant reduces substantially the cost of incorporating this process into the plant scheme.

The estimated investment (I) and operation and maintenance (O&M) costs of the unit processes and operations for the wastewater flow rates studied in each case are presented in Tables 4–11, along with the breakdown of the related economic data. The estimated costs seem to be in agreement with construction costs of wastewater treatment facilities reported in the literature, although the differences in construction costs of diverse countries have to be taken into account (Fuog *et al.* 1995; Siegrist 1996; Haruvy 1997; Papaiacovou 2001; Chen and Chang 2002). Figures 3 and 4 present the I and O&M costs as functions of wastewater flow rate for the four WWTPs studied, respectively. Naturally, both costs increase with required wastewater treatment level for any flow rate; however the incremental cost for the operation of a T_4 – WWTP (potable water effluent standard) relative to a T_3 – WWTP is greater than that between a T_3 – WWTP and a T_2 – WWTP. The cost curves of Figures 3 and 4 have been fitted by the functions $I(€) = A\,Q^{n}$ and $O\&M(€\,m^{-3}) = -\alpha \ln Q + \beta$, respectively, where Q ($m^3\ h^{-1}$) is the flow rate and A, n, α and β are empirical parameters. Table 12 presents the values for these parameters as functions of wastewater treatment level. These equations can be useful in estimating the costs of WWTPs as a function of flow rate and required treatment level.

SUMMARY AND CONCLUSIONS

The effectiveness and the cost of wastewater treatment strategies appropriate for different uses of reclaimed water, including irrigation, aquifer recharge by infiltration and by direct injection, in seasonally stressed regions have been evaluated. The wastewater treatment options studied are applicable to locales of the semi-arid regions of the Mediterranean rim and islands with water demand stressed mainly from seasonally intense tourism and agriculture. Process decision and design criteria suitable for the raw wastewater of locales with large transient population and seasonally stressed conditions (flow rate, waste strength and toxicity), destination of the reclaimed water, with corresponding discharge standards and relevant economics have been considered for the specification of wastewater treatment plants. A set of cost functions for investment and operation and maintenance developed based on technical design and cost estimation of the unit processes and operations of the studied wastewater treatment plants has been proposed.

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REFERENCES

Asano, T. 1985 *Artificial Recharge of Groundwater*. Butterworth Publishers, Boston, Massachusetts.

Asano, T. & Cotruvo, J. A. 2004 Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. *Wat. Res.* **38**(8), 1941–1951.

Bachmat, Y. 1994 Groundwater as part of the water system. In: Zoller, U. (ed.) *Ground Water Contamination and Control*. Marcel Dekker, Inc, New York.

Botzan, T. M., Necula, A. I., Mariño, M. A. & Basagaoglu, H. 1999 Benefit-cost model for an artificial recharge scenario in the San Joaquin Valley, California. *Wat. Resour. Managmt* **13**(3), 189–203.

Broens, L., Liebrand, N., Futselaar, H. & Armas Torrent, J. C. 2004 Effluent reuse at Barranco Seco (Spain): a 1,000 m^3/h case study. *Desalination* **167**, 13–16.

Chen, H. W. & Chang, N. B. 2002 A comparative analysis of methods to represent uncertainty in estimating the cost of constructing wastewater treatment plants. *J. Environ. Managmt* **65**, 383–409.

Custodio, E. & Bruggeman, G. A. 1987 Salt–fresh water interrelationship under natural conditions. Effect of human activities on salt–fresh water interrelationships in coastal aquifers. In: Custodio, E. & Bruggeman, G. A. (eds) *Groundwater Problems in Coastal Areas*. UNESCO – IHP, Paris, pp. 14–112.

Donovan, D. J., Katzer, T., Brothers, K., Cole, E. & Johnson, M. 2002 Cost-benefit analysis of artificial recharge in Las Vegas Valley, Nevada. *J. Wat. Resour. Plann. Managmt* **128**(5), 356–365.

Ergil, M. E. 2000 The salination problem of the Guzelyurt aquifer. *Wat. Res.* **34**, 1201–1214.

Fuog, R. M., Giberson, K. C. & Lawrence, R. L. 1995 Wastewater reclamation at Rancho Murieta, California; Golf course irrigation with upgraded pond effluent meeting California's strictest requirements for wastewater reuse. *Wat. Sci. Technol.* **31**, 399–408.

Georgopoulou, E., Kotronarou, A., Koussis, A., Restrepo, P. J., Gómez-Gotor, A. & Rodríguez Jiménez, J. J. 2001 A methodology to investigate brackish groundwater desalination coupled with aquifer recharge by treated wastewater as an alternative strategy for water supply in Mediterranean areas. *Desalination Journal* **136**, 307–315.

Haruvy, N. 1997 Agricultural reuse of wastewater: nation-wide cost-benefit analysis. *Agric. Ecosyst. & Environ.* **66**, 113–119.

Kanarek, A. & Michail, M. 1996 Groundwater recharge with municipal effluent: Dan Region Reclamation Project, Israel. *Wat. Sci. Technol.* **34** (11 pt 7), 227–233.

Koussis, A. D. (ed.) 2001 *WASSER: Utilisation of Groundwater Desalination & Wastewater Reuse in the Water Supply of Seasonally-Stressed Regions*. Final Report. National Observatory of Athens.

Koussis, A. D., Kotronarou, A., Destouni, G. & Prieto, C. 2002 Intensive groundwater development in coastal zones and small islands. In: Llamas, R. & Custodio, E. (eds) *Intensive Use of Groundwater: Challenges and Opportunities*, Balkema, The Netherlands, Chapter 6, pp. 133–155.

Koutsoyiannis, D. & Baloutsos, G. 2000 Analysis of a long record of annual maximum rainfall in Athens, Greece, and design rainfall inferences. *Natural Hazards* **29**, 29–48.

Lee, E. W. 1990 Drainage water treatment and disposal options. *Am. Soc. Civ. Engrs, Man. Rep. Engng Practice* **71**, 450–468.

McCutcheon, S. C., Martin, J. L. & Barnwell, T. O., Jr 1993 Water quality. In: Maidment, D. R. (ed.) *Handbook of Hydrology*, Chapter 11. McGraw-Hill, New York.

Metcalf and Eddy, Inc. 1991 *Wastewater Engineering*, 3rd edn. McGraw-Hill, New York.

Montgomery, J. M. 1985 *Water Treatment: Principles and Design*. John Wiley & Sons, New York.

Papaiacovou, I. 2001 Case study: Wastewater reuse in Limassol as an alternative water source. *Desalination* **138**, 55–59.

Pollice, A., Lopez, A., Laera, G., Rubino, P. & Lonigro, A. 2004 Tertiary filtered municipal wastewater as alternative water source in agriculture: a field investigation in Southern Italy. *Sci. Total Environ.* **324**, 201–210.

Rushton, K. R. & Phadtare, P. N. 1989 Artificial recharge pilot projects in Gujarat, India. In *Groundwater Management: Quantity and Quality*. IAHS Publication No. 188, Benidorm, pp. 533–545.

Salgot, M. & Pascual, A. 1996 Existing guidelines and regulations in Spain on wastewater reclamation and reuse. *Wat. Sci. Technol.* **34**(11), 261–267.

Siegrist, H. 1996 Nitrogen removal from digester supernatant: Comparison of chemical and biological methods. *Wat. Sci. Technol.* **34**, 399–406.

Water Environment Federation 1991 *Design of Municipal Wastewater Treatment Plants*. Manual of Practice No. 8, vols I and II. Water Environment Federation, Alexandria, Virginia.

Water Environment Federation 1992 *Water Reuse*. Water Environment Federation Digest Series, Alexandria, Virginia.

Water Pollution Control Federation 1989 *Water Reuse: Manual of Practice*. Manual of Practice SM-3, 2nd edn. Water Pollution Control Federation, Alexandria, Virginia.

WEF & AWWA (Water Environment Federation & American Water Works Association) 1998. *Using reclaimed water to augment potable water resources*. Joint Task Force.

World Bank 1995. Middle East and North Africa environmental strategy towards sustainable development. Report No. 13601-MNA. Washington, D.C.

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