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Review

Artificial Recharge via Boreholes Using Treated Wastewater: Possibilities and Prospects

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Abstract: Interest in artificial recharge of groundwater using pretreated wastewater continues to increase, especially in semi-arid countries. After the artificial recharge and natural treatment, the water could be extracted through boreholes pumping for direct irrigation. The selection of suitable locations for artificial recharge should be based on hydrogeological conditions, economic evaluation and environmental considerations. Clogging of boreholes that are used for artificial recharge is a serious problem and requires proper planning to reduce it. This paper deals with the investigation of the possibilities and prospects of aquifer recharge via boreholes using treated wastewater. Firstly, the aquifer recharge techniques, the proposed criteria of waste and the clogging effect are presented. Secondly, the possibility of application of artificial recharge in the South-Eastern Mesaoria aquifer of Cyprus is examined. Based on hydrogeological results, artificial recharge using tertiary treated wastewater via boreholes is one of the options available for increasing the groundwater reserves of this aquifer. The recycled water will infiltrate through gravel pack, providing favorable conditions for ventilation and laminar flow due to small water flow velocity. The treatment works include the removal of the fat, oil and grease (FOG) and cyanides (CN^-) content in order to meet the upper acceptable limits.

Keywords: artificial recharge; clogging effect; Cyprus; groundwater; Mesaoria aquifer; treatment; wastewater

1. Introduction

Groundwater is actually under strong human pressures in many countries. Such pressures include changes in land use, urbanization, intensive agriculture and water demand increase and can cause severe degradation of the quality and quantity of groundwater resources [1]. The degradation of groundwater resource can be quantitative and qualitative, if the abstraction exceeds the natural recharge rate. The use of groundwater resources has become particularly intensive in coastal areas during the last decades with intense urbanization, touristic development and irrigated land expansion. As a result, a negative water balance is established in the coastal aquifer systems triggering sea water intrusion which has negative consequences in the socioeconomic development of these areas. Many aquifer systems are reported to be affected by depletion and quality deterioration (salinization and nitrate pollution) due to irrational management. For this reason recycled water is a new source of water that must be taken into account in planning integrated water resources management [2]. Treated water is a valuable water resource and should be taken into account in designing a rational water policy.

Artificial recharge or aquifer recharge with reclaimed wastewater effluents has been successfully used worldwide to control water depletion in overexploited aquifers [3-5]. Preliminary estimates show that the implementation of wastewater recycling and reuse projects would lead to water savings of up to 5% of the total irrigation water [6]. A limiting factor in applying groundwater recharge is the lack of suitable site selection. Artificial recharge using treated wastewater in depleted aquifers, via deep boreholes, is an internationally acceptable practice, which is compatible with the 2000/60/EC directive and may contribute to cover a part of irrigation needs, as well as the sustainable water resources management in many areas [7].

The main environmental issue associated with artificial recharge is the degradation of subsurface environment and groundwater due to the transport of pathogenic viruses with the recycled water. Furthermore, the clogging effect of boreholes caused by suspended solids, bacterial and recharge water is a phenomenon that limits the viability of artificial recharge.

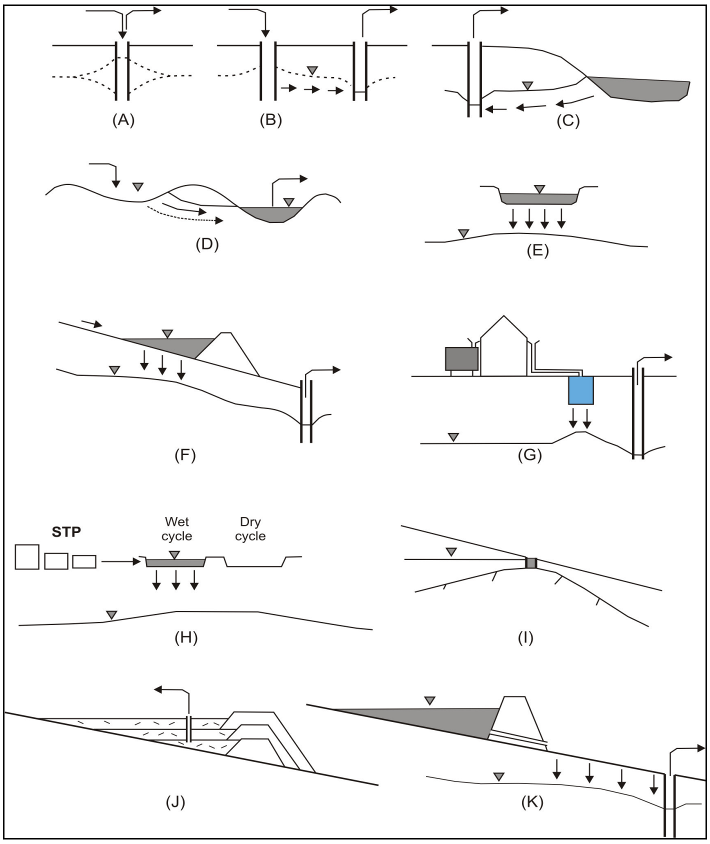
The objective of this paper is to investigate the possibilities and prospects of aquifer recharge via boreholes using treated wastewater. Furthermore, the clogging effect and the possibility of application of artificial recharge in the South-Eastern Mesaoria aquifer (Cyprus), using reclaimed wastewater is examined.

2. Aquifer Recharge Techniques

Aquifer recharge is a useful tool for groundwater resources management in order to guarantee their sustainability. It could be a solution for declining groundwater levels and depletion of aquifers, saline intrusion, land subsidence and for water harvesting and reuse.

As shown in Figure 1, the types of aquifer recharge are [8]: Aquifer storage and recovery (A), Aquifer storage transfer and recovery (B), Bank filtration (C), Dune filtration (D), Infiltration ponds (E), Percolation tanks (F), Rainwater harvesting (G), Soil aquifer treatment (H), Underground dams (I), Sand dams (J), and Recharge releases (K).

Figure 1. Different types of aquifer recharge [8] (with modifications).



Aquifer storage and recovery (ASR) includes injection of water into a borehole for storage and pumping from the same borehole. Aquifer storage transfer and recovery (ASTR) includes injection of water into a borehole for storage and pumping from a different borehole. Generally, ASTR provides additional water treatment, as well as the longer the residence time in soil, the more opportunity for interaction with biological, chemical, and physical processes that can decrease pollution potential.

Wastewater reuse via percolation ponds has been practiced in many regions, e.g., Israel (Dan Region Reclamation project), Belgium (St. André), USA (California), Australia, Egypt, *etc.* [9]. The Dan Region Reclamation Project in Israel has been in operation for the last 35 years and the reclaimed water is used for agricultural irrigation. A system of infiltration ponds in the coastal aquifer was used. The ponds are located on sand dunes, up to 3–4 m thick and the infiltration procedure is conducted in cycles of 3–4 days [10]. The reclaimed water is pumped by boreholes surrounding the infiltration basins and is transported for irrigation.

Field experiments proved that the wastewater quality could be improved by infiltration ponds. The processes responsible for the improvement of quality are: biological and chemical reactions, absorption and filtration in unsaturated zone. The increase in Total Dissolved Salts (TDS) can be attributed to the leaching of salts from the vadose zone of the aquifer [11].

Artificial recharge via boreholes is carried out in the following steps [7]:

(a) Site investigations in order to determine the hydrogeological conditions, including depth to groundwater level, type of aquifer, direction of groundwater flow, hydraulic parameters of aquifer, *etc.*

(b) Determination of groundwater and injected (treated wastewater) water quality and treatment processes to meet required standards.
(c) Water injection via boreholes. The optimum rate must range between the 1/3 and 1/2 of the maximum pumping rate [12].
(d) Monitoring. Detailed groundwater levels could be measured in the piezometers of the recharge boreholes, as well as in other observation boreholes/piezometers. In addition, measurements and/or automatic recording of the groundwater level should be undertaken to determine the recharge cone, based on a monitoring net of neighboring piezometers and boreholes. For the observation of the possible alteration of the chemical characteristics of the groundwater, chemical analyses should be carried out before and after the recharge application.
(e) Management of clogging effect.

3. Wastewater-Proposed Criteria

Reuse of wastewater combined with artificial recharge offers alternate solutions in many countries in the frame of integrated water resources management. The wastewater should be pre-treated to improve its physico-chemical characteristics. Tsagarakis *et al.* [6] have proposed guidelines for recycled water, as are given in Table 1.

Table 1. Proposed criteria for groundwater recharge using reclaimed wastewater in Greece [6].

Physicochemical parameter	Proposed value
Intestinal Nematodes *	≤1 eggs/L
Fecal Coliform	≤100 cfu/100 mL
Total Suspended Solids	≤10 mg/L
Total Nutrient	<15 mg/L
Minimal depth of groundwater	5 m

* includes the families: Strongyloides, Trichostrongylus, Toxacara, Enterobius and Capillaria.

It is pointed out that no water reuse regulations exist in the European Union. The only reference to it is in article 12 of the European Wastewater Directive 91/271/EEC [13] suggesting "Treated wastewater shall be reused whenever appropriate" [6]. In order to improve the wastewater quality, membrane filtration techniques could be applied [14]:

- Ultrafiltration is the first treatment step, removing suspended solids and bacteria from the wastewater.
- Reverse osmosis is the final treatment step, removing salts, nutrients, viruses and small organics (pesticides).

4. Clogging Effect

Clogging of boreholes that are used for artificial recharge is a well-known phenomenon and caused by [15-17]:

(1) Recharge Water

The high concentration of recharge water in gas bubbles is an important factor to reduce the yield of artificial recharge via boreholes or wells. Clogging with gas bubbles can be avoided by keeping the pressure in the system above the total dissolved gas pressure and by refraining from throttling the flow [18].

(2) Bacteria

Clogging due to bacteria takes place when the amount of Assimilable Organic Carbon (AOC) in the recharge water is high enough to facilitate bacterial growth around the borehole. Pretreatment of water recharge should be applied to reduce the content of AOC.

It is pointed out that one major concern with using recycled water is that active/infective human enteric viruses might be delivered with the recycled water in the subsurface environment [19]. Recent investigations suggested that a 40-log removal of viruses would occur within 150 m of passage through a fine to coarse, moderately sorted sand aquifer [20]; on the other hand, in a fractured aquifer the required most conservative set back distance for drinking wells should be over 8 Km [21].

(3) Chemical Reactions

Chemical clogging can be caused by different chemical actions within an aquifer system and depends on hydrogeological conditions and water quality, e.g., the calcite dissolution is an important geochemical process occurring around the borehole and might limit the life of boreholes.

The precipitation of iron hydroxides is one possible cause of well clogging in the case of mixing water containing oxygen without Fe^{2+} with water containing Fe^{2+} and no O_2 nor NO_3. When pH ranges are between 7 and 8, the following fast reaction takes place around the borehole screen [22,23]:

$$O_2 + 4Fe^{2+} + 8HCO_3^- + 2H_2O \rightarrow 4Fe(OH)_3 + 8CO_2$$

A similar reaction takes place with the presence of nitrate, at a slower rate:

$$0{,}2NO_3^- + Fe^{2+} + 1{,}8HCO_3^- + 0{,}6H_2O \rightarrow Fe(OH)_3 + 0{,}1N_2 + 1{,}8CO_2$$

Recovery boreholes close to injection boreholes may clog due to iron(hydr)oxides, which are produced by mixing of waters. This problem can be avoided by increasing the distance between recovery and recharge boreholes.

During the movement of water, oxidation of organic matter and CO_2 production occurs with simultaneous consumption of O_2 according to the reaction:

$$CH_2O + O_2 \leftrightarrow CO_2 + H_2O$$

After the depletion of O_2, denitrification is the next process [22]:

$$4NO_3^- + 5CH_2O + 4H^+ \leftrightarrow 2N_2 + 5CO_2 + 7H_2O$$

Usually during the movement of groundwater the concentration of ions Ca^{2+} and HCO_3^- increases, due to the dissolution of calcium carbonate ($CaCO_3$):

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$$

Carbon dioxide CO_2 comes from oxidation of organic matter. Addition of carbon dioxide through oxidation of organic matter can also induce calcite dissolution. Calcite ($CaCO_3$) dissolution may increase the hydraulic conductivity in the vicinity of borehole due to the development of secondary porosity, but may restrict the effective life of an artificial recharge system.

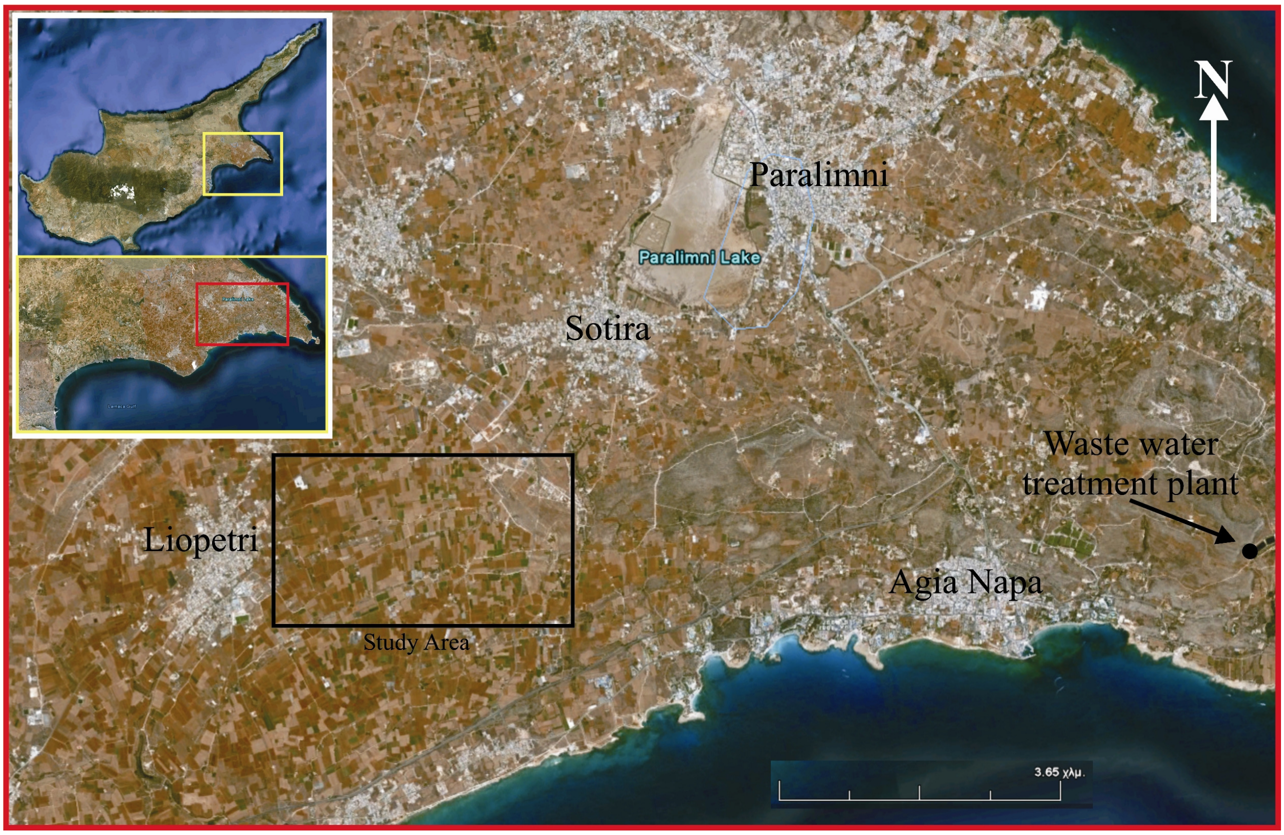
(4) Suspended Matter

Clogging of the boreholes by suspended solids (SS) is not expected to affect the viability of the artificial recharge, if the recycled water contains SS levels ≤ 3–4 mg/L [17]. Based on previous studies [16] it is concluded that suspended solids clogging can be satisfactorily controlled by backwashing for 10 min after injection of 10 ML of water containing SS < 1 mg/L.

5. Case Study

The study area is located south of Liopetri village, part of the South-Eastern Mesaoria basin (Kokkinochoria), Cyprus. It covers an area of about 6 Km^2 (Figure 2). The upper part consists of secondary limestone compact crust (kafkala) and soft secondary limestone (chavara). The average thickness of the aforementioned limestone is 6 m. The presence of kafkala constricts the infiltration of water to the deeper aquifers. Sandstones and sandy facies are observed at depth 30–45 m below ground surface [24,25]. The area is characterized by semiarid climate conditions; the mean annual rainfall is 320 mm, occurring in the wet period (November-April). High water demands are recorded in dry period, when the availability of water is low.

Figure 2. Location of the study area (Adapted from Google Earth with modifications).



The main aquifer system is developed from sandstone horizons and sands. Overpumping during the last decades through a large number of boreholes has caused a decline of groundwater level and the occurrence of negative piezometry up to 30 m below mean sea level. As a result, sea intrusion phenomena are recorded for distance up to 1–2 Km inland in the northern part.

The average thickness of the unsaturated zone, below sea level, is 25 m, whereas the average thickness of rocks of the unsaturated zone above sea level is 50 m. The thickness of the saturated zone depends on the local hydrogeological conditions and the pumping regime ranging between 1–5 m. In general, the direction of groundwater flow is from the North to South and is controlled by the creation of depression cone in the areas where overpumping takes place.

Based on results of the chemical analyses of five samples from boreholes (January 2009) it is concluded that: Electrical conductivity at 25 °C ranges from 700 μS/cm to 3150 μS/cm and chloride concentration ranges from 130 to 220 mg/L. High values of electrical conductivity and chloride concentration can be associated with the seawater intrusion in the southern part of the study area [26].

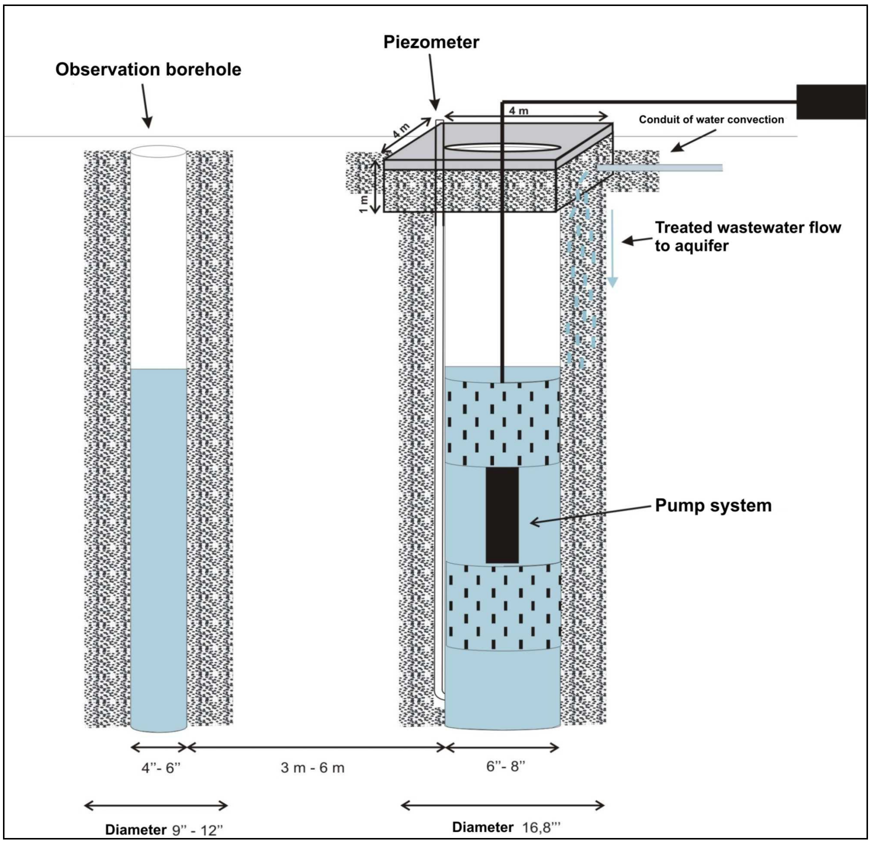
In most parts of the aquifer the yield of boreholes has been reduced (<3 m^3/h), because of the reduction of the saturated thickness of the aquifer and a lot of boreholes or wells are useless. The average hydraulic conductivity value is $k = 2.6 \times 10^{-6}$ m/s, as deduced from the conducted pumping long test analyses. Based on the values of hydraulic conductivity and the depth of the aquifer layers, the mean transmissivity was estimated to be $T = 18$ m^2/day. The stabilization discharge of groundwater level during the constant head tests varies between 6 m^3/h and 20 m^3/h [26]. It should be mentioned that the aquifer hydraulic conductivity of subsurface formations can be significantly degraded due to retention of viable and inactivated biocolloids (bacteria and viruses) suspended in reclaimed wastewater [20].

The average thickness of the aquifer is up to 80 m and the maximum 120 m and it is characterized by quality degradation and depletion during the last decades. Artificial recharge using tertiary treated wastewater via deep boreholes is one of the options available for increasing the groundwater reserves in the South-Eastern Mesaoria aquifer. The maximum annual recharge volume of the aquifer system through 90 recharge boreholes is estimated to be 3.2×10^6 m^3 water [26].

Aquifer recharge using treated wastewater has the potential to provide new and low cost source of water, especially for irrigation use and to prevent the seawater intrusion in the study area. The data from the operation of the Agia Napa Wastewater Treatment Plant (WWTP) shows that there is, in general, surplus of recycled water (260,000 m^3/year) in regard to the irrigation and/or other needs of the two communities (Agia Napa and Paralimni, see Figure 2) served by the plant. The maximum daily capacity of WWTP is 21,000 m^3.

Clogging during artificial recharge increase the water table in the borehole and reduces the recharge rate. Based on geological conditions of the study area, a schematic installation is shown in Figure 3, in order to minimize the clogging effect. The recycled water will infiltrate through gravel pack, providing favorable conditions for ventilation and laminar flow due to small water flow velocity [26].

Figure 3. Proposed installation of the recycled water recharge system via deep borehole [26].



Regarding the quality of the recycled water (based on the results of chemical analyses from samples at the exit of WWTP), it appears to be overall adequate for its designated uses. However, some parameters seem to exceed the desired limits [26]:

Conductivity and chlorides (Cl^{-}): The values for these two parameters are higher (average of 1700 μS/cm and of 460 mg/L, respectively) than the desired values as determined in the Directive 75/440/EEC (limit values for surface water to be used for drinking purposes). Nevertheless, since the recycled water is eventually used for irrigation purposes the average values could be considered acceptable.

Cyanides (CN^{-}): Very high concentrations of cyanides (5–7 mg/L) were measured in the recycled water (upper acceptable limit 0.05 mg/L). The high values of cyanides in combination with the increased level of COD (61 mg/L) and the high values of fat, oil and grease (FOG) in the recycled water, indicate that industrial type of wastewater is illegally discharged in the sewer system of Agia Napa and Paralimni, which could originate from various type of industrial activities (metal processing, photographic and printing activities, production of synthetic rubber, production of adhesives, production of paints, pharmaceutical activities, leather treatment, production of animal food and agricultural pesticides/biocides, production of detergents, mining activities and from wineries).

Fat, oil and grease (FOG): The constant exceedances of the WWTP's specification limit value (5 mg/L), regarding the FOG content in the recycled water (mean value 18.8 mg/L), was due to the absence of an oil separator in the treatment process.

The mean value of trace elements concentration is: B (0.55 mg/L), total Fe (0.02 mg/L), Mn (0.004 mg/L), Se (<0.008 mg/L), F (<0.3 mg/L), Al (0.2 mg/L), Cr^{3+} (<0.003 mg/L), Li (<0.15 mg/L), Co (<0.002 mg/L), Mo (0.0016 mg/L).

The treatment works include the following [24]:

Removal of FOG and cyanides (CN^-) content in order to meet the aforementioned limits: These treatment options are designed to treat the entire recycled water produced from the WWTP. Two separate lines are designed for the treatment of recycled water produced by Agia Napa and by Paralimni, respectively. Each unit consists of a Dissolved Air Flotation (DAF) unit for the removal of FOG and of an alkaline oxidation unit for the removal of cyanides.

Ultrafiltration of surplus of recycled water:

This treatment option refers to all scenarios under consideration and is designed to treat the surplus of recycled water that is used for the recharging of the aquifer. It is designed to be constructed in three phases in accordance with the drilling of the recharging boreholes. The ultrafiltration treatment is followed by disinfection with NaOCl solution.

6. Conclusions-Discussion

Artificial recharge using treated wastewater, via deep boreholes, is an internationally acceptable practice, which is compatible with the 2000/60/EC Directive and may contribute to cover a large part of irrigation needs, as well as sustainable water resources management in many countries. Thus, it could be a solution for regions with low water availability and deteriorating water quality due to saline water intrusion.

The process of selecting suitable locations includes: hydrogeological conditions, availability and quality of wastewater, possible benefits, economic evaluation and environmental considerations [27].

The wastewater should be pre-treated to improve its physico-chemical characteristics [28]. The pre-treatment includes ultrafiltration and/or inverse osmosis. Membrane techniques are successful in producing wastewater with low values of TDS and nutrient content.

Injection borehole clogging can occur within hours to years after the start of an artificial recharge project, reducing the injection rate and increasing the water level in the injection borehole. An operational clogging control strategy should be designed aimed at retardation of occurrence and reduction of the degree of clogging in the recharge borehole. On the other hand, the reuse of wastewater requires that farmers should overcome the psychological barrier [29]. It is pointed out that in many countries the farmers avoid using reclaimed wastewater for irrigation purposes. Criteria for the safe use of treated wastewater should be established in order to maximize public health protection, to ensure that the recovered water meets the guidelines for quality chemical and microbiological analyses. Furthermore, special educational programs for stakeholders should be adopted.

Based on preliminary results, artificial recharge using tertiary treated wastewater via boreholes is one of the options available for increasing the groundwater reserves in the South-Eastern Mesaoria aquifer. The aforementioned results of the case study demonstrated the feasibility of artificially recharging the aquifer system of Liopetri area (Cyprus), via deep boreholes, using pre-treated wastewater.

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