Promoting on-site urban wastewater reuse through MBR-RO treatment

A. Plevri*, D. Mamais**, C. Noutsopoulos**, C. Makropoulos**, A. Andreadakis**, K. Rippis*, E. Smeti*

* Athens Water and Sewerage Company S.A (E.Y.D.A.P.) – Research and Development – Oropou 156, 11146, Galatsi, Athens, Greece
**Sanitary Engineering Laboratory, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 9, Zografou 157 80, Athens, Greece.

Abstract
A compact membrane bioreactor and reverse osmosis (MBR-RO) system was installed in KEREFYT, EYDAP, in order to assess the potential reuse applications of the reclaimed water. The feed of the unit was directly drained from the sewage network. The objective of the study was to examine the effluent's water quality. This was performed through a series of lab measurements as well as from data taken by a series of on-line sensors installed in several points of the unit. This paper discusses the presence of contaminants, biological and chemical, in the MBR's permeate, as well as the RO's effluent, thus determining the system's efficiency. This study has shown that the MBR-RO system can produce a high quality water. The RO effluent's quality in terms of organic content (0,9 mg/L BOD_5 and not detectable TSS), Ammonium (0,25 mg/L), Total Nitrogen (12 mg/L), turbidity (0,32 NTU), E. Coli (not detectable) and Total Coliforms (not detectable) could fully meet the water quality requirements for reclaimed water, as dictated by the Greek legislation. However, it is considered necessary to conduct further tests in order to be totally in line with the Greek legislation. The remaining parameters that have to be measured are heavy metals, microorganic pollutants and priority pollutants.

Keywords
Sewer mining; Water reuse; Wastewater reclamation; Membrane bioreactor; Reverse osmosis; MBR/RO

1. INTRODUCTION

Due to global climate change and rapid population growth, there has been a worldwide effort to reduce water demand. Substitution of fresh water for non-potable uses with water from alternative sources such as rainwater or treated blackwater and greywater is being encouraged so as to reduce fresh water demand. Latest wastewater recycling invention called sewer mining is gradually increasing in popularity due to its high treatment efficiency as well as the fact that less space is required to install the unit. Sewer mining does not use conventional wastewater treatment methods, but alternative ones that enable the usage of a compact, portable and advanced treatment unit. Moreover, direct sewer mining can reduce the need for additional infrastructure and ongoing energy consumption to transmit wastewater to a centralized treatment facility and then recycled water to the point of use (Marleni *et al.*, 2013).

An innovative small footprint sewer mining packaged treatment unit for urban reuse enabled by Advanced Monitoring Infrastructure (AMI) and Decision Support System (DSS) has been placed in KEREFYT, EYDAP, in the Metamorphosi region (Athens, Greece). Athens demo site tests the idea of sewer mining as a concept for distributed reuse within the urban environment, exploiting state-of-the-art Information and Communication Technology solutions for distributed monitoring and management. Reused water characteristics and their impacts on soil are also being tested, via onsite irrigation of urban green. Finally, the demo site is examining a major component of ecosystem services (ESS) specifically relevant for arid regions: the mitigation of heat island effects due to irrigation of urban green. This is performed through sprinkler irrigation -with the unit's reclaimed water- on a grass field, located near the unit.

The main advantages of the sewer mining unit installed in the Athens demo site are:

- the production of high quality recycled water due to the combination of biomembrane reactor with reverse osmosis, conforming to stringent performance criteria, including health and water quality standards,
- the minimum landscape disruption due to the small size of the unit coupled with the lack of odours and noise pollution, making it suitable for installation in the urban environment,
- the fully independent function of the system provided by the installed automations, as well as the online monitoring system that ensures a high quality of the treated water stream and
- the ability of direct mining of sewage from the network, close to the point-of-use, with minimum infrastructure required and low transportation costs for the treated effluent.

The objective of this pilot trial is to evaluate the quality of the effluent and to explore the feasibility of reclamation and reuse of the treated effluent as specified in the Greek National legal framework for urban reuse and specifically article 6 of the JMD 145116/2011 referring to quality levels and treatment processes.

2. MATERIALS AND METHODS

2.1. Description of the pilot-scale MBR-RO process

A dual-membrane process, such as an ultrafiltration (UF) and reverse osmosis (RO), is becoming increasingly attractive owing to the technology used for the reclamation of municipal wastewater because of its efficiency as well as its simple and economical operation. In such a process, UF is used for the treatment of secondary effluent prior to RO. The suspended solids are removed by UF while the RO removes dissolved solids, organic and ionic matters. A membrane bioreactor can achieve both the secondary treatment of sewage as well as the pretreatment for RO, and hence MBR-RO has a great potential for the treatment of raw sewage to produce reclaimable water (Yang, 2009; Xiao *et al*., 2014).

In DESSIN's pilot unit, feedwater is pumped from the local sewerage network to the satellite wastewater treatment plant. The inlet pumping station is feeding the sewage through a preliminary treatment that includes a compact fine screen-grit system and a biotube filter in the equalization tank of the system. The screens allow for the retention of solids and the grit-grease unit for the protection of the downstream equipment from sand particles and grease and oil. The outlet flow from the pretreatment unit enters via overflowing to the main treatment units. The main treatment units consist of biological treatment with MBR and finally an RO unit (Figure 1).

The denitrification stage comes first and consists of an anoxic tank equipped with a proper mixing device that ensures mixing of the liquor. The mixed liquor from the denitrification tank enters the aeration tank where the biological processes of oxidation of the organic load, nitrification and stabilization of sludge take place.

The method chosen is the separation of the mixed liquor from the treated effluent by a system with ultrafiltration membranes. Hollow fibers ultra filtration modules for MBR plant operate under negative pressure with a filtration direction going from the outside of the hollow fiber towards the inside. Solids are therefore withheld in the retentate on the outside of the hollow fibers while the permeate flows inside and is collected by the collection manifold in the module to be subsequently conveyed to a permeate accumulation tank and then discharged. Excess sludge returns to sewage network. Discharge to wastewater collection system is a viable consideration where the retentate comes from a satellite treatment facility and the volume of the retentate is relatively small compared to the total flow of the central wastewater treatment plant.

Cleaning of the membranes with air (air scouring) is performed through an aeration system that consists of blowers and coarse bubble diffusers. This operation protects the membranes from fouling and also ensures the smooth operation of the system, by removing the deposited -on the membranes- particles, thus allowing the filtration of the incoming wastewater (Lioumis, 2015).

In order to maintain membrane permeability, two more ways of membrane cleaning have been applied. The first one is the backflushing mode, where the extraction pump inverts its rotation sense and conveys a part of permeate produced from the inside to the outside of the hollow fibers to detach any material that may have been deposited on the outer surface of the fibers or inside the pores during the suction period. The second one is maintenance cleaning; chemical cleaning cycles consisting of NaOCl (Sodium hypochloride) and Citric acid, that reach the membranes by backflushing clean water that is enriched with those chemicals through dosage pumps.
After leaving the membrane section, the permeate is driven into a tank by a lobed pump. From that tank it ends up to the RO system. RO systems are practically required to be incorporated in the treatment train (following MBR system) especially in the case of wastewater with high salinity. The need for RO as a post treatment level derives from the necessity to comply with the environmental standards as in the case of saline wastewater. Moreover, the unit has the ability to work without RO treatment, in which case the permeate ends up directly into the effluent tank. A schematic of the pilot plant is presented in Figure 1(Judd, 2006).

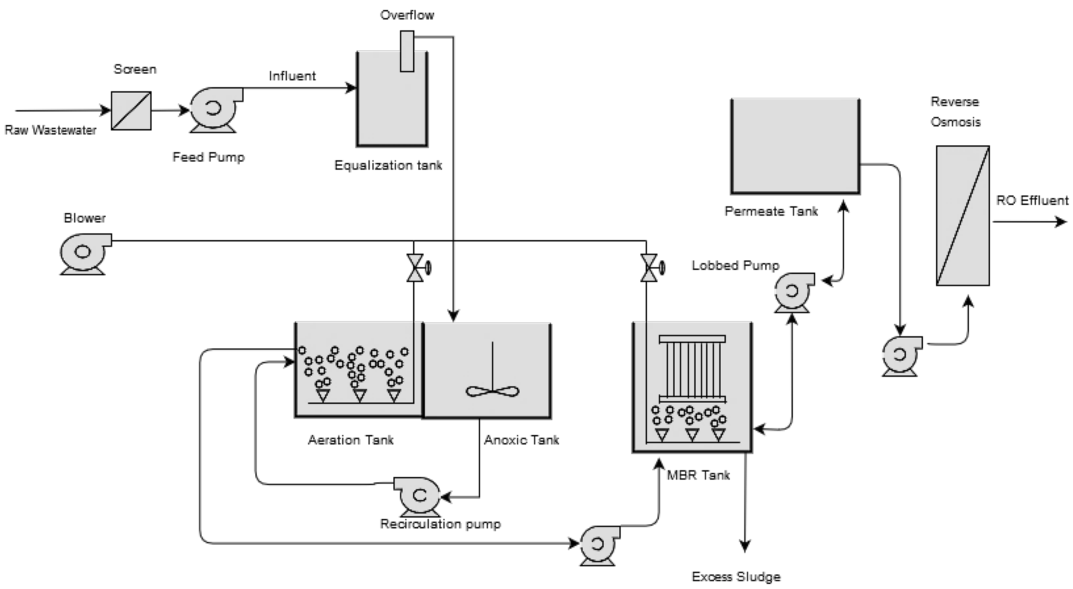

Fig. 1. Schematic of the MBR/RO pilot plant

Fig. 2. Presentation of DESSIN's pilot plant. The left photograph depicts the compact unit containing (from the left to the right) the MBR, aeration, anoxic and equalization tanks, while the right one shows the Reverse Osmosis.

2.2. Operating parameters and monitoring systems

The pilot unit has been set in operation for 8 months. During this period, temperature varied between 15-25^{o}C. The capacity of the unit was set to 10 m^3 of treated water per day, while it has been designed to be able to reach 100 m^3. The concentration of mixed liquor suspended solids (MLSS) in the MBR tank was controlled between 8-9 g/L with daily removal of excess sludge, while the same variable inside the anoxic and aeration tank had a value of around 6 g/L. Moreover, the sludge age (SRT) was set to 20 d.

An operation cycle of MBR involved a 10 min filtration and a 1 min backflushing mode in order to preserve the permeability. The maintenance cycles include one oxidizing cleaning per day and one acid maintenance per week. Table 1 presents the estimated chemical reagent consumption for membrane regeneration for the maintenance cycles.

Table 1: Maintenance cleaning protocol

	Quantity (g/cycle)	Duration (min)
NaOCl(14%)	43	30
Citric Acid(30%)	340	40

One of the main advantages of the unit is the ICT integration which allows constant control and monitoring of the system by uploading data on an online platform. In order to control the quality of the process and the effluent, a series of on-line sensors have been installed at several key points of the unit, to provide perpetual information about the integrity of the operation. More specifically, a conductivity meter has been installed in the inlet, permeate and RO effluent tank, a pH sensor in the RO effluent and membrane tank, a turbidity sensor in the permeate tank, an MLSS sensor in the membrane tank, a DO sensor in the aeration tank and finally a nitrate & ammonium sensor in both the anoxic and aeration tank.
Apart from using on-line sensors, a series of laboratory analyses provide feedback for the unit and many of them are used for cross validation with the sensor measurements, thus providing feedback

on the status of the sensor. The laboratory analysis takes place twice a week, and includes measurements of COD, CODs, SS, VSS, SVI, BOD, TP, TN, NH_4-N^+, NO_3-N^-, Cl^-, TC, EC.

3. RESULTS AND DISCUSSION

In order to promote the MBR-RO pilot system as a viable solution for non-potable water needs, especially in arid areas or highly urbanized environments, its excellent effluent water quality must be highlighted. To do so, both the operational performance and the water quality of the MBR and RO were evaluated. Furthermore, cross validation of the produced water quality and the one demanded by the Greek legislation for water reclamation was also performed.

3.1 Overall performance

The unit started functioning in January 2016 without any biomass inoculation. The startup process lasted approximately 5 weeks, in which the necessary conditions were met for biomass development and nitrification-denitrification processes started taking place.

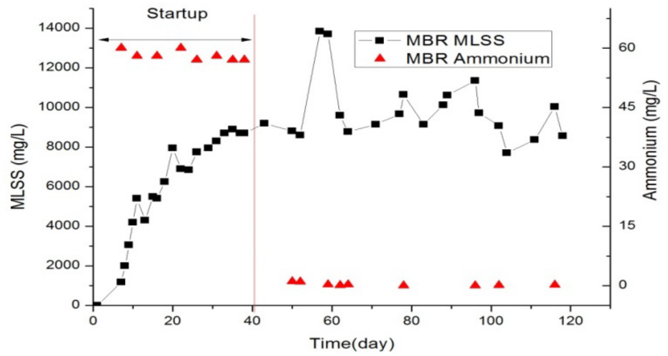

Fig. 3. Start-up period of the unit

By examination of the initial stages of the unit, the biotube seems to be acting efficiently as a filter for the removal of oils and other substances that can be proven harmful for the biomembranes. This can be seen from the reduction of the COD from the degritted waste stream to the filtered waste stream, presented in Figure 4. Finally, the raw wastewater characteristics appear to have significant fluctuations.

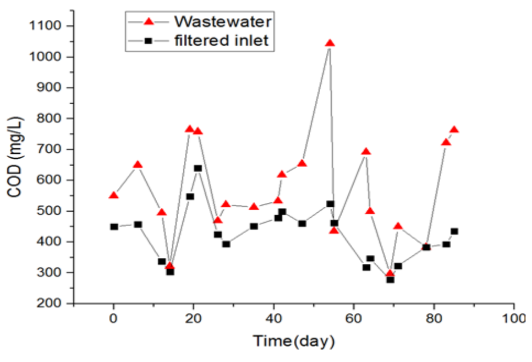

Fig. 4. COD of raw and pretreated wastewater

The characteristics of the feed water and the filtered water entering the equalization tank are listed in the Table 2.

Table 2: Characteristics of degritted and filtered wastewater

Parameters	Mean Value (Standard Deviation)	
	Degritted Sewage	Filtered sewage
TSS(mg/L)	376(373)	164(72)
VSS(mg/L)	235(112)	138(46)
COD(mg/L)	578(176)	424(86)
CODs(mg/L)	173(30)	171(25)
TP(mg/L)	10(0,97)	8,8(0,76)
NH_4-N^+(mg/)	57(18)	55 (15)
Cl^-(mg/L)	184(98)	157 (23)

The performance of the MBR/RO unit was regularly monitored in terms of operation and treated water quality. MBR alone was able to bring down the concentrations of most of the pollutants under acceptable limits for water reuse applications. Despite the fluctuations in the influent characteristics the MBR showed stable effluent characteristics. The application of RO further improved the treated water quality, especially the aesthetical and microbial quantities.

3.2. MBR performance and permeate quality

The whole operation of the MBR was stable and its performance was satisfactory. The online data from the sensor showed that the turbidity never exceeded the value of 2 NTU, while the average value was around 0.3 NTU. The effluent BOD was always below 2 mg/L, while the average effluent COD was only 23 mg/L with a very high removal, averaging around 95% (Figure 5(b)). Moreover, the nitrification process is almost complete, with ammoniacal nitrogen concentrations reaching zero (Figure 5(d)). The removal of 0suspended solids is complete, being always below the limit of detection of the analytical method, due to the fact that the particle size is way bigger than the one of the membrane pores, so the particles are unable to penetrate through the membrane section. This utter discharge is one of the benefits of the MBR system against conventional systems, which instead of using sedimentation tanks for the same cause, leading to a very low organic load in the effluent, since it is not burdened with particulate load. Adding to that, the ensured stability of the permeate is of high importance for the smooth operation of the Reverse Osmosis, making the MBR system ideal pretreatment to RO. Finally, the fact that the TSS in the MBR permeate stream were negligible within the 3 months evaluation span (as well as in the whole 8 month period), as seen in Figure 5 (a) as well as the fact that transmembrane pressure (TMP) has a steady value of 2 kP indicate that the membrane remains intact, without evident fouling (Comerton, 2005).

Throughout the operation period, all the key qualitative values have remained steady in the permeate flow, proving that the backflushing mode and the maintenance cleaning have been very successful in maintaining the integrity of the membrane. That’s the reason why so far recovery cleaning hasn’t been necessary.

In Table 3, certain critical units that refer to the effluent of both MBR and RO are listed. Among them, it is evident that the microbial pollution is drastically reduced, although MBR seems unable to totally eliminate it. Figure 5 shows several characteristics of the permeate. Looking at Figure 5 (c), it is clear that the unit operated at values of MLSS over 8000 mg/L and despite the fact that the tank is small (1,5 m^3), that value has a certain stability. Moreover, it is of high importance that the sensors provide trusted data, as it is seen from the cross validation with the lab measurements. The accurate sensor measurements are very important as they allow the remote control of the unit and they provide its safety by leading to alarm conditions and ultimately to unit shutdown –if needed- when key values overcome the programmed upper threshold (Malamis, 2009).

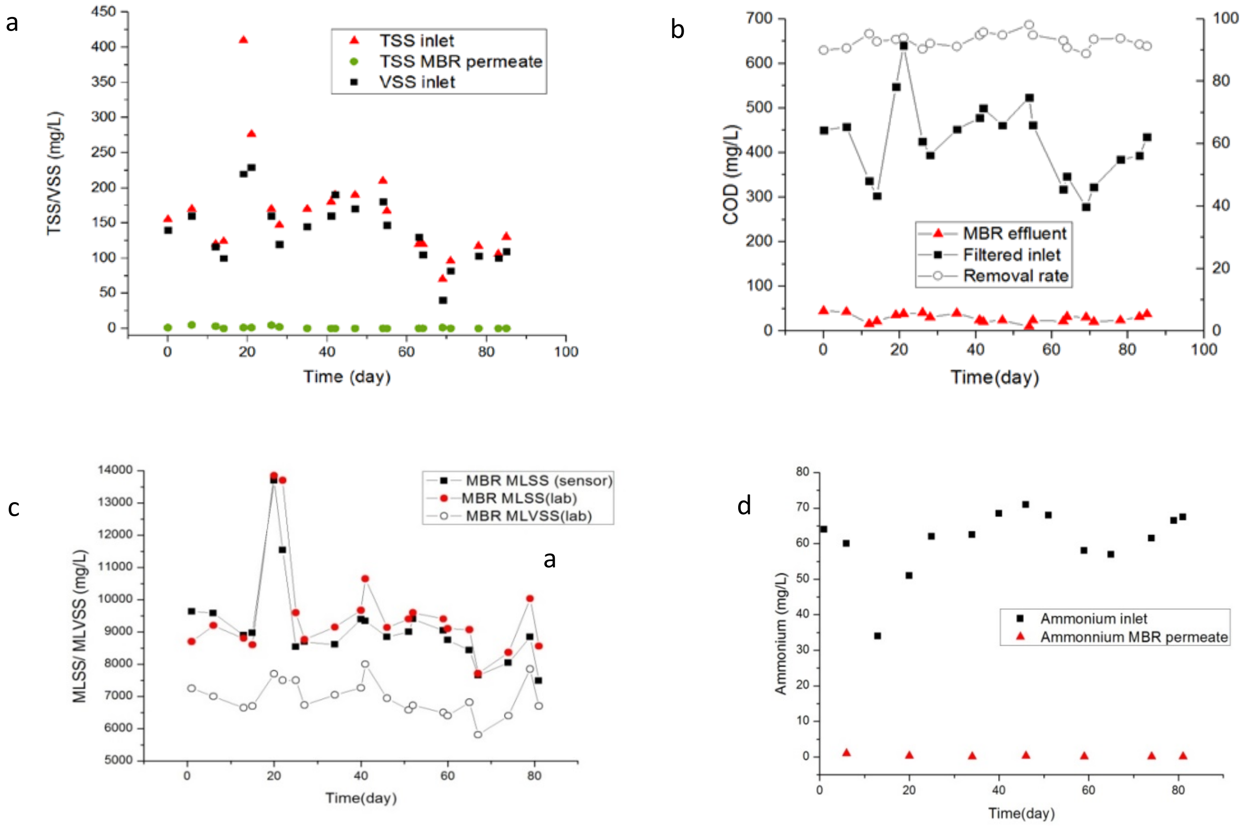

Fig. 5. MBR performance in (a) TSS, (b) COD, (c) MLSS and (d) Ammonium

3.3. RO performance and effluent quality

The performance of the reverse osmosis is such that superior water quality was achieved in the effluent. First of all, as seen in Table 3, all the microbial pollutants remain under the limit of detection of the analytical methods. The RO effluent did not show any presence of *E.Coli* or Total Coliform, indicating their complete rejection. Moreover, chlorides are less than a quarter in comparison with the RO inlet. Other parameters than remain under the detection limit are COD and Total Phosphorus. Generally, the data prove that the RO effluent quality in terms of organic content, Ammonium, Total Nitrogen, turbidity, *E. Coli* and Total Coliforms could fully meet the water quality requirements for reclaimed water, as dictated by the Greek legislation (Table 3).

The installed on-line sensors monitor the pH and conductivity of both the inlet and effluent of the RO. Conductivity is the single most important and most commonly monitored system parameter in an RO plant. The RO flux and recovery rate are greatly affected by the conductivity of the feed water. As conductivity rises, the same happens with osmotic pressure, thus making the RO system less efficient at a given pressure and temperature. That’s why the sensors position and function there are of great importance, since they make it possible to identify changes in permeate flow rate due to feed conductivity fluctuations (Tam, 2007).

Conductivity remains unaffected by the MBR, but was drastically reduced by the reverse osmosis. In order to evaluate the performance of the RO in terms of effluent pollutant concentrations, rejection in terms of conductivity was used, which is defined as the percentage difference between the conductivity of the feed water and that of the effluent. The rejection averages at values over 90% (Figure 6(b)). The same behavior, unaffected by the MBR but drastically diminished by the RO, applied for the pH (Figure 6(a)). Another conclusion deducted by Figure 6 is that both conductivity and pH of the RO effluent keep rising in time while rejection rate decreases. This indicates that the RO membranes have sustained fouling or scaling, although anti-scalants were inserted regularly –through dosing pumps- into the system in order to minimize chemical precipitation on the RO membrane surface (Witgens, 2005).

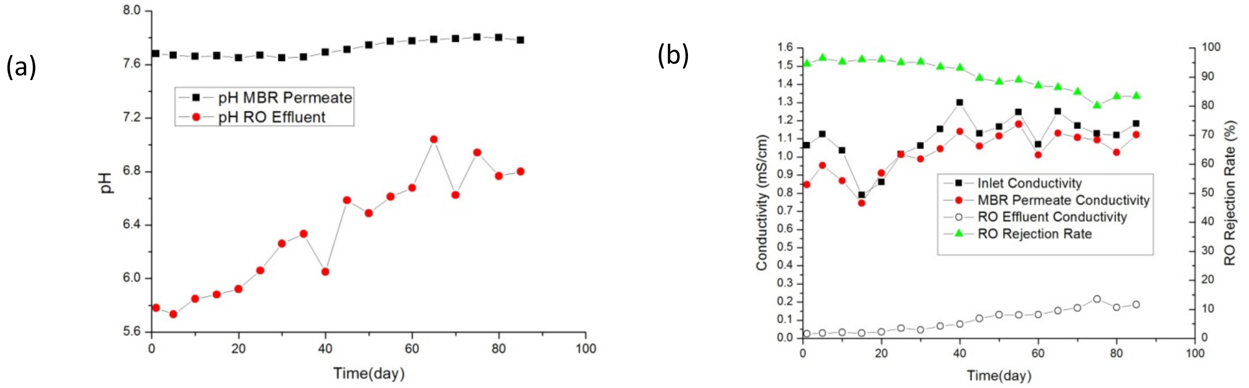

Fig. 6. pH and conductivity data referring to the RO effluent, retrieved by the installed sensors

Table 3: Performance of the MBR-RO pilot unit (JMD 145116, 2011).

Parameters	Mean Value (Standard Deviation) MBR effluent	RO effluent	Legislation limits
TSS (mg/L)	<5	<5	≤2
VSS (mg/L)	<5	<5	-
COD (mg/L)	23(9,53)	<10	-
CODs (mg/L)	29(10)	<10	-
BOD_5 (mg/L)	0,9	0,8	≤10
TP (mg/L)	5,9 (1,2)	<0,5	
TN	-	12(7,8)	≤15
NH_4-N^+ (mg/L)	0,25(0,32)	-	≤2
Cl^- (mg/L)	172(75)	42(24)	≤100 for sprinkler irrigation
Turbidity (NTU)	0,32 (0,1)	-	≤2
Total Coliform (cfu/100ml)	307 (393)	ND	≤2
Faecal Coliform (cfu/100ml)	1,09 (1,86)	ND	-
E.Coli (cfu/100ml)	0,82 (0,98)	ND	≤5

4. CONCLUSIONS

Double-membrane treatment schemes allow municipal wastewater to be upgraded to a quality suitable for many reuse purposes The MBR-RO technology was proved to treat the wastewater with satisfactory system stability and high contaminant removal efficiency. The MBR effluent met the quality requirement of RO feed, while the RO permeate met the reuse water standards as dictated by the Greek legislation, while further improving microbial and aesthetical quantities. So far, transmembrane pressure (TMP) remains steady and at low values, proving that the combination of backflushing with maintenance cleaning is very effective. The removal of COD and microbial pollutants was total. However, total nitrogen and total phosphorus were drastically removed by the RO, which means that reuse for irrigational purposes might be better with an MBR followed by UV treatment for further reducing pathogen concentration, while maintaining beneficial for the plants nutrients.

One of the planned steps is the cleaning of the RO membrane, since the data from the sensors show corrosion marks. Furthermore, in order to deduct more solid conclusions about the reclaimed water's quality and to be in line with Greek legislation, it has been plant that in the near future, the following parameters will be measured: heavy metals, microorganic & priority pollutants. In addition to that, studies must be made concerning the deposit excess sludge of the MBR unit that so far returns to the sewage network. Another future step is the optimization of the unit's energy consumption.

ACKNOWLEDGMENT
The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement no 619039 (ENV.2013.WATER INNO&DEMO-1), for the research project DESSIN "Demonstrate Ecosystem Services Enabling Innovation in the Water". The research and its conclusions reflect only the views of the authors and the European Union is not liable for any use that may be made of the information contained herein.

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