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Research article

Sewer-mining: A water reuse option supporting circular economy, public service provision and entrepreneurship

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A B S T R A C T

Water scarcity, either due to increased urbanisation or climatic variability, has motivated societies to reduce pressure on water resources mainly by reducing water demand. However, this practice alone is not sufficient to guarantee the quality of life that high quality water services underpin, especially within a context of increased urbanisation. As such, the idea of water reuse has been gaining momentum for some time and has recently found a more general context within the idea of the Circular Economy. This paper is set within the context of an ongoing discussion between centralized and decentralized water reuse techniques and the investigation of trade-offs between efficiency and economic viability of reuse at different scales. Specifically, we argue for an intermediate scale of a water reuse option termed ‘sewer-mining’, which could be considered a reuse scheme at the neighbourhood scale. We suggest that sewer mining (a) provides a feasible alternative reuse option when the geography of the wastewater treatment plant is problematic, (b) relies on mature treatment technologies and (c) presents an opportunity for Small Medium Enterprises (SME) to be involved in the water market, securing environmental, social and economic benefits. To support this argument, we report on a pilot sewer-mining application in Athens, Greece. The pilot, integrates two subsystems: a packaged treatment unit and an information and communications technology (ICT) infrastructure. The paper reports on the pilot's overall performance and critically evaluates the potential of the sewer-mining idea to become a significant piece of the circular economy puzzle for water.

1. Introduction

The global urbanization trend has resulted in a constant increase of urban populations. In Europe, for example, the percentage of the urban population is 73.4% of the total and is expected to rise up to 81% by 2050 (UN, 2014a,b). This trend is coupled with water scarcity due to supply-side impacts of climatic changes (Klein et al., 2014) and improving living standards (UNESCO, 2016) resulting in increased pressures on water resources. For this reason, recent EU reports stress the need to encourage European stakeholders to first acknowledge that “water is an essential but limited resource and needs to be carefully allocated and used”, and then to endorse and promote circular and green economies (EUWA, 2014).

Turning waste into a resource is an essential part of increasing the efficiency of resources and moving towards a more circular economy (EC, 2015). In the context of the urban water cycle, this translates primarily into using treated wastewater (a waste) to supply (as a resource) a (more often than not) non-potable water use. This can be implemented at several scales, associated with the degree of centralisation of the treatment employed (Libralato et al., 2012).

At the more centralised scale, the use of tertiary treatment in

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existing wastewater treatment facilities can open up non-potable reuse options, especially in large water consumers such as agriculture or industry. Indeed, notable examples of such large-scale reuse include cases in Spain (Mujeriego et al., 2008), Israel and Australia (Jimenez and Asano, 2008). However, as centralised wastewater treatment plants are by definition close to the urban centres they service, they are not necessarily close enough to agricultural or industrial activities and as such the construction and operation of treated effluent conveyance systems can rival in costs even desalination.

Decentralized technologies on the other hand, by their very nature (i.e. *in situ* installation), are closer to the circular economy concept, in that by closing the loop between waste and resource locally, waste water becomes not ‘just’ a by-product of the urban water system with some potential for reuse, but a resource *per se*, also decreasing (or eliminating) the barrier of transmission costs.

Decentralized water recycling technologies come in a wide variety of options and scales (Rozos and Makropoulos, 2012). At the lowest scale, in-house units treat water from the hand-basin, shower and bath and provide this water for use in the toilet, washing machine and for outside uses (Dixon et al., 1999; Leggett et al., 2001). The problem at this scale is that the maintenance and operational costs are very high to allow economically viable schemes and as such, this scale of reuse (termed greywater reuse (Li et al., 2009)) usually relies on additional motivation, such as drought conditions or positive environmental attitudes of individuals at the household level (Koutiva and Makropoulos, 2016). On the other hand, greywater recycling at a larger scale, the cluster or neighbourhood scale (e.g. Paris and Schlapp, 2010), has much lower running costs but requires extensive work for the installation of dual reticulation, which unless installed during the construction phase, results in considerable costs.

Sewer-mining is a less known option in the toolbox of decentralized wastewater reuse technologies at an intermediate (local-to-neighbourhood) scale. It extracts wastewater from local sewers, treats it at the point of demand and supplies local non-potable uses (such as urban green irrigation) while returning treatment residuals back to the sewer system (Butler and MacCormick, 1996) for eventual treatment in the centralised wastewater treatment plant thus eliminating the need for both expensive conveyance systems from end of pipe treatment installations and dual reticulation infrastructure.

This type of technology was pioneered in Australia to provide non-potable water for urban uses, including for example the irrigation of urban green spaces, sport facilities and even domestic uses (AEDCS, 2005; Sydney Water, 2013; Chanan and Woods, 2006; Fisher, 2012; Xie et al., 2013). Table 1 displays some successful applications of sewer-mining in Australia with capacities ranging from 100 to over 2000 m^3/d. It is worth noticing that apart from the application in Darling Quarter, where the entire treatment system is fitted within a room in the building's basement and extra care had to be taken to ensure no malodour, the average cost of reclaimed water is very close (if not lower) to potable water costs.

Despite the existence of sewer-mining success stories in Australia, several challenges remain currently in the way of such applications in Europe, including public perception, inadequate regulatory frameworks, engineering issues, as well as, importantly, financial constraints. Euro-zone GDP in the final quarter of 2015 was still below its pre-crisis peak of early 2008 whereas America's was almost 10% above its peak of late 2007 and Australia's almost 60% (The Economist, 2016). For this reason, the European Commission has launched an investment plan for Europe to unlock over EUR 315 billion of investment over the next few years and deliver a powerful and targeted boost to economic sectors that create jobs and raise growth (EC, 2016). Regarding the water sector, a GDP growth around 0.2–0.6% is expected as a result of water industry investments alone, to achieve compliance with the WFD (EC, 2015). It therefore becomes evident that this period is quite favourable in Europe for the kind of entrepreneurship that combines circular/green economies with water management.

In this study, we suggest that recent technological advancements, regarding both wastewater treatment and smart ICT technologies, offer an opportunity for Small Medium Enterprises (SME) to become a principal actor in the water reuse sector, creating a real market for water reuse services and increasing its applications in the EU. Specifically, we argue that Sewer-mining could develop into a win-win situation whereby the benefits of market competition will be brought to bear in the water sector due to the ability of SMEs to manage sewer-mining units and sell the treated wastewater (or indeed irrigation services) to city municipalities, while water companies also benefit being able to sell untreated sewage, or at least have some of their wastewater treated at no cost to them. All in all, two major objectives set by the European Commission regarding (i) economic growth (new investments, new jobs, etc.) and (ii) environmental protection (reduce the pressure on water resources while increasing ecosystem services such as heat island effect reduction through urban green irrigation even in water scarce areas) stand to benefit from an adoption of sewer-mining as a dominant form of urban treated wastewater reuse.

To support this argument, what is doubtlessly needed is a demonstration of the technology's ease of deployment, operational efficiency and viability in terms of its business model. In this paper, we present the configuration and operation of a prototype sewer-mining unit, piloted in the city of Athens, Greece, highlighting the

Table 1
Sewer-mining applications in Australia.

Location	Technology	Capacity	Use	Cost
[a]Flemington Racecourse Melbourne, Australia	Dual membrane, UV	100 m^3/d	Irrigation	Estimated unit capital cost 0.42 \$/m^3, operational cost 0.43 \$/m^3, prices 2006
[b]Darling Quarter, Sydney's CBD Australia	Moving bed, biofilm reactor, RO, UV	170 m^3/d	toilet flushing, irrigation, cooling towers	unit capital cost 2.2 \$/m^3 operational cost 2.1 \$/m^3, prices 2011
[c]Riverside Rocks Park, Sydney, Australia	Reed beds, UV	360 m^3/d	Irrigation	estimated unit capital cost 0.49 \$/m^3, prices 2006
[d]Pennant Hills, North Sydney, Australia	MBR, UV	1000 m^3/d	Golf field irrigation	estimated unit capital cost 0.49 \$/m^3, prices 2008
[e]Sydney Olympic Park	SBR, nutrient	2191 m^3/d	Toilet flushing, irrigation	cost 1.05 \$/m^3, prices 2009 (90% the price of potable)

[a] Clearwater (2016).
[b] ISF (2013).
[c] McFallan and Logan (2008).
[d] WERF (2008).
[e] Listowski (2009).

following characteristics:

- Availability of state-of-the-art solutions based on a fusion of the most recent ICT with wastewater treatment technologies enabling remote control of multiple units;
- Ease of deployment taking into account both treatment constraints and use of the water produced requirements;
- Generality of the approach that enables straightforward application to a variety of cases requiring a calibration of only a minimal set of parameters;

Finally, to support and facilitate the transferability of sewer-mining to a variety of cases, we report on two tools, developed to support design and deployment at different scales. These tools, described in the following sections, include a) an urban water cycle model that can be used not only to estimate the demand of non-potable potable water but also the ecosystem services of using the recycled water (e.g. the reduction of the urban heat island effect) and b) a model that helps in the identification of potential locations for deployment of sewer-mining units at the neighbourhood/region/city scale.

2. Methods

2.1. Treatment unit

The sewer-mining unit consists of two sub-units; the Membrane bioreactor (MBR) and the Reverse Osmosis (RO) unit. Both have been constructed as individual packaged modules that are joined together in one compact system offering ease of transportation. The capacity of the unit is 10 m^3/d.

In the MBR, a circulation stream of sludge keeps in balance the biological solids around the membranes. This recirculation stream is rich in dissolved oxygen (2.5–5.0 mgO_2/L) and provides to the nitrification zone supplemental oxygen for the biological processes. This stream also prevents the sludge de-watering in the filtration tank and additionally reduces the fouling of the membranes by reducing the TSS load at the membrane. The circulation rate regulates the biomass concentration, which should not exceed a maximum threshold. MBR operation requires that this stream is 4 times the net permeate flow. The latter suggests an overall sludge circulation flow of 40 m^3/d during the peak flow.

For the maintenance of the membrane, the standard suction required for sludge filtration is periodically interrupted for a back-flush and/or a relaxation cycle ("Cleaning in place"). Both back-flush and relaxation cycles are executed automatically by the operation software. In order to preserve membrane permeability, it is also required to run chemical cleaning cycles on the membrane. The chemical cleaning procedures have been scheduled to run daily, weekly (short duration and low concentration cleanings) and yearly (performed manually, requires soaking times from 8 to 12 h). An air system with a blower exists to help in this procedure.

The MBR sub-unit is contained in a 2.16 × 2.00 × 2.87 m^3 box, which is divided into five compartments where the treatment sub-processes take place. These compartments serve also as tanks (buffers) that allow a variation (between a minimum and a maximum operational level) of the sewage volume that is treated at any time. The numbers 1 to 5 appearing in orange circles in Fig. 1 correspond to the tanks where the various processes of the sewage treatment take place.

1. In the primary tank, floating and settling substances are removed. The sewage from this tank passes, via a coarse filter, to the denitrification tank for further treatment whereas the collected materials are removed via the drain.
2. In the denitrification tank, nitrate reduction takes place thanks to the organic substrate of the influent sewage. This tank is equipped with underwater mixer which keeps the sludge suspended and uniformly mixed. This is actually a mixture of return sludge and raw wastewater. This mixture is pumped to the nitrification tank (P2 in Fig. 1).
3. In nitrification tank both oxidation of the organic substance and nitrification of ammonium nitrogen take place simultaneously. The nitrification zone is equipped with an air distribution system where fine bubbles both keep the nitrification reactor in aerobic conditions and keep the content uniformly mixed. The aeration process is conducted in a non-homogenous way inside the oxidation reactor. In detail, the air distribution line is submerged into the tank and is controlled automatically according to the dissolved oxygen concentration, which is measured by DO sensors. This makes the system more flexible and more energy-efficient regarding the biological processes. The air injection line is positioned upstream of the terminal section of the nitrification tank, in sufficient distance from the pump feeding the membrane tanks (P3 in Fig. 1), so as not to disturb its smooth operation. This pump is an immersed pump at low pressure head.
4. In the membrane tank, permeate is extracted through the membrane (to be further treated in the RO sub-unit, see blue line originating from membrane in Fig. 1) via a positive displacement lobe pump. This pump is reversible to allow periodic back-flushing operation. The permeate system discharges into the final storage permeate tank. At least 300 L of storage are required to carry out the various back-flushing operations of the membranes and the automatic routine maintenance cleaning steps with chemicals. A part of the sludge of the membrane tank is pumped to the final tank (P6 in Fig. 1) whereas the rest part overflows back to the nitrification tank.
5. In the final tank, the final settlement takes place and the sludge is drained from the bottom. In case of excess sludge, this tank overflows. The outflows from this tank (drain plus any overflows) along with the drains from primary tank are the sludge coming out from the sewer-mining unit, which should be returned to the sewer.

The effluent of the MBR is further treated with an RO. The RO skid along with the required electromechanical equipment and the controllers of MBR and RO are located inside a second 2.16 × 3.00 × 2.87 m^3 box, adjacent to the MBR box (see Fig. 2). Table 2 gives the expected quality indicators of the MBR and the RO effluents against the influent sewage.

2.2. Automated monitoring – remote controlling

Sensing elements, data collection instruments and control devices are integrated into an ICT smart platform (Karagiannidis et al., 2016). 'Sensing' here refers to, *inter alia*, field sensors (for both wastewater and treated effluent), heat/temperature and energy sensors with which the compact unit is equipped. These are integrated to field sensor porting means and coupled with a targeted communications solution, which provides a self-organizing and autonomous wireless network set-up, linking local events to the control centre. More specifically, the ICT platform offers the following services to support the operation of the compact treatment unit:

- local/remote access and control of the sensors,
- inspection of sensor metadata (e.g. location, time etc.),
- real-time data retrieval and display,
- detection of events of interest (alerts can be triggered),

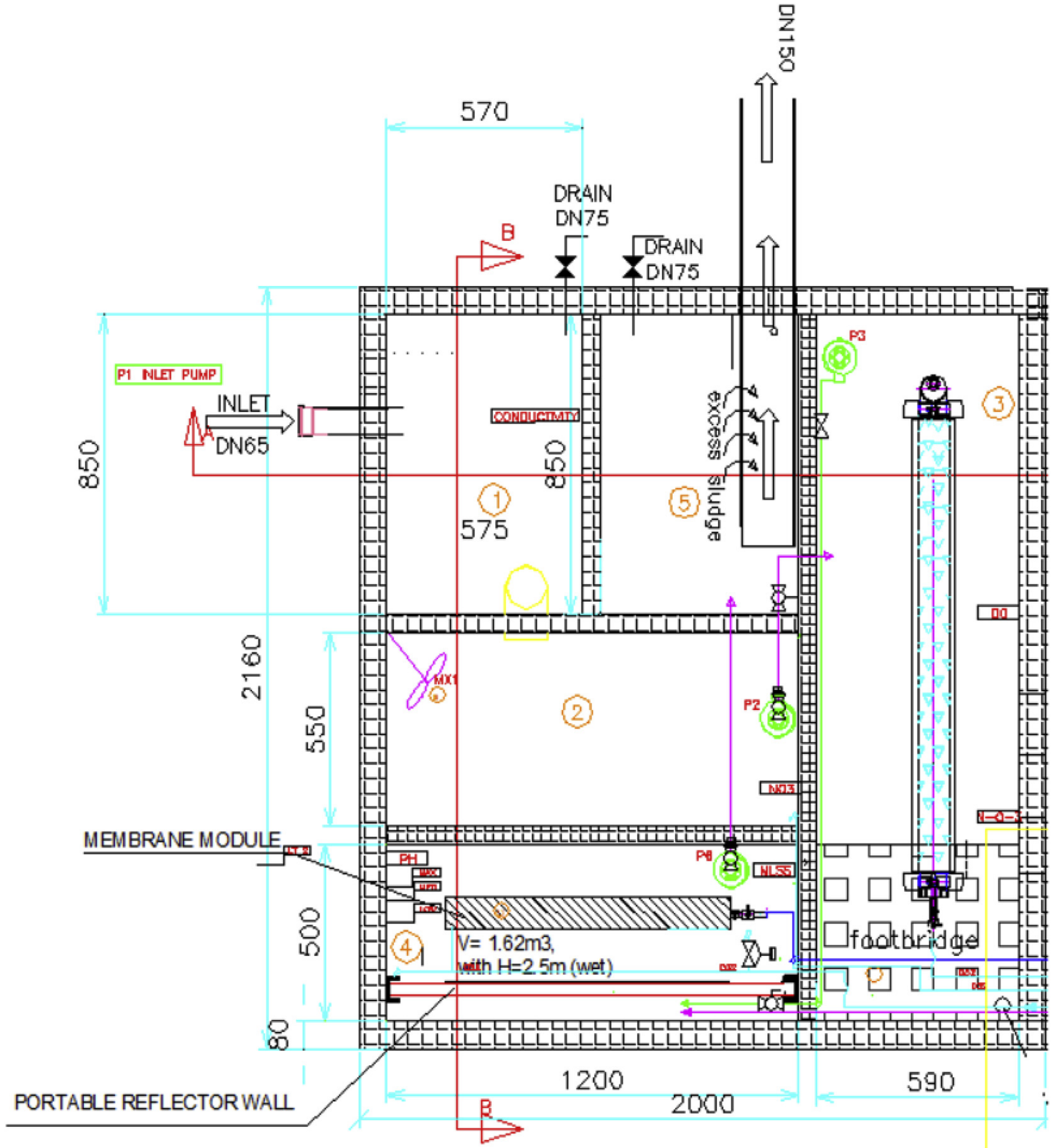

Fig. 1. Membrane bioreactor plan view (dimensions in mm).

- manipulation of the stored timeseries (insert, delete, edit),
- queries to historical data (e.g. based on predefined date and time period),
- visualization of the sensor data (e.g. different colour schemes and charts)
- reports in various formats (e.g. .txt, .xls, etc.)

The platform architecture is displayed in Fig. 2. Twenty-one physical and chemical characteristics (see Table 3) are measured using 10 sensors. These sensors are connected to a sensor controller (consists of two probe modules and one display module), which turns the signals received from the sensors into digital data, displays and logs the measurements. To enable remote retrieval of this data and remote configuration of the sensors, the sensor controller is connected to a micro-controller via an RS485 to USB adaptor employing MODBUS protocol. The micro-controller is a Raspberry Pi (a low cost, credit-card sized computer) running a Linux server. This Linux server communicates with the main server via a wireless network (it can be Ethernet or 3G in other applications). The main server is a desktop PC that hosts the web platform and offers to the remote and local users' access to the service.

For the automation of electromechanical processes (operation of pumps, blowers, mixers, valves etc.), a programmable logic controller (PLC) is used. Specifically, a Vision1210 (by Unitronics) PLC is used to automate the following functions:

- change unit from “Manual Mode” to “Auto Mode”,
- control and modification of supplies (VALUES Q) by setting minimum and maximum flow transmitter values,
- monitoring of alarms/alerts generated by the PLC,
- monitoring of tank level,
- monitoring of mixers and blowers, and control of timers,
- monitoring and control of pumps, valves and flow meters,
- monitoring and control of pressure transmitters,
- control of “Cleaning in Place” function.

To enable the remote controlling of the PLC, the PLC is connected via a Wi-Fi to the main server. Fig. 3 displays the main screen used

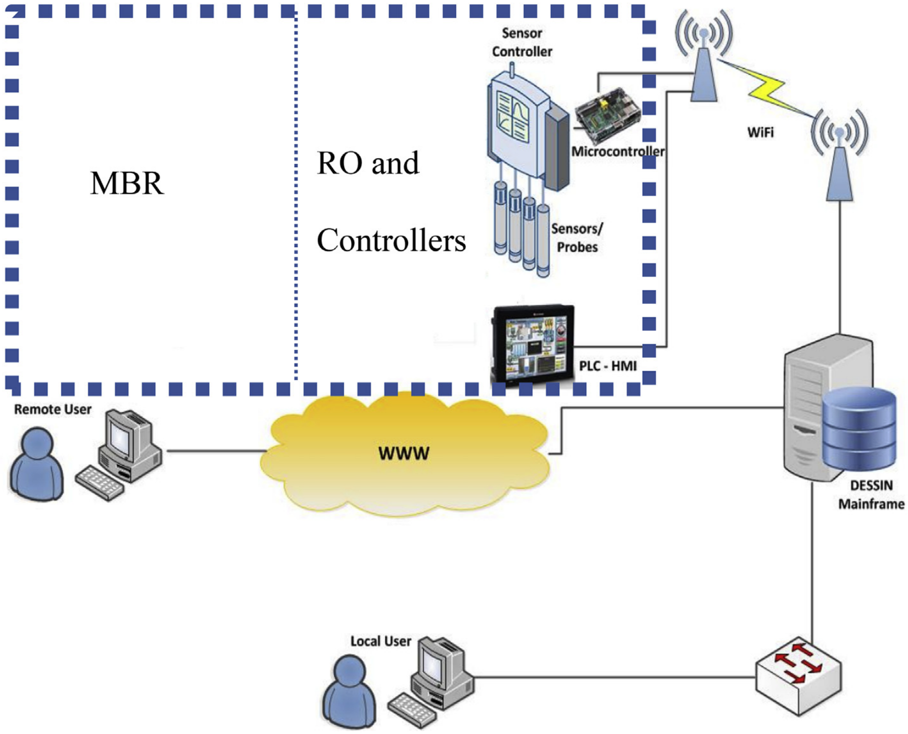

Fig. 2. System architecture of the smart ICT platform.

Table 2
Quality indicators after MBR and after RO sub-units.

Indicator	Sewage	MBR	RO
BOD_5 mg/L	154	≤10	≤1
COD mg/L	341	≤70	≤5
TSS mg/L	146	≤5	nil

Table 3
Measured physical and chemical characteristics in sewer-mining unit.

Location	Code	Index	Units
Inlet	DL0_S8_1	Conductivity	mS/cm
Inlet	DL0_S8_2	Temperature	°C
Anoxic Tank	DL0_S7_1	Nitrate	mg/L
Anoxic Tank	DL0_S7_2	Chloride	mg/L
Anoxic Tank	DL0_S7_3	Temperature	°C
Aeration Tank	DL0_S3_1	DO	mg/L
Aeration Tank	DL0_S6_5	Temperature	°C
Aeration Tank	DL0_S6_1	Ammonium	mg/L
Aeration Tank	DL0_S6_2	Nitrate	mg/L
Aeration Tank	DL0_S6_3	Potassium	mg/L
Aeration Tank	DL0_S6_4	Chloride	mg/L
Aeration Tank	DL0_S6_5	Temperature	°C
Membrane Tank	DL0_S0	MLSS[a]	mg/L
Membrane Tank	DL0_S9_1	PH	pH
Membrane Tank	DL0_S9_2	Temperature	°C
Permeate Tank	DL0_S1	Turbidity	NTU
Permeate Tank	DL0_S5_1	Conductivity	mS/cm
Permeate Tank	DL0_S5_2	Temperature	°C
RO Effluent	DL0_S4	PH	pH
RO Effluent	DL0_S2_1	Temperature	°C
RO Effluent	DL0_S2_2	Conductivity	mS/cm

[a] MLSS: Mixed liquor suspended solids.

to control the PLC. The user can read in this screen the volume stored in all tanks of the MBR (primary, denitrification, nitrification, membrane, sludge, and permeate) and RO systems, the flow pumped between any two tanks, and the air pressure of any blower. The chemicals and the equipment of the cleaning system are also displayed in this screen.

All this information is processed into the main server, which runs the software that integrates all related functions under one platform. This software, named Protocol Adapter, is based on the OGC-SWE standards (Open Geospatial Consortium – Sensor Web Enablement). Protocol Adapter is responsible for the communication of the server with the micro-controller to get the measurements from the sensors. Then, Protocol Adapter translates these raw measurements into XML files, according to the OGC standard. These XML files are processed by the Sensor Observation Service (to obtain observations from one or more sensors) and by the Sensor Event Service (to obtain alerts, i.e. notifications regarding measurements outside the nominal range). Finally, these two services send their outputs (in SensorML format) to the Data Fusion Engine, which, after the necessary analysis, transforms them to web format (JSON) and pass them to the Web Platform.

Fig. 4 displays the web interface used to monitor the operation of the compact unit. In this screen timeseries of the permeate tank temperature, and instant values of permeate tank turbidity and conductivity are displayed (provided by the Sensor Observation Service). Along these values, alarms concerning the corresponding sensors are displayed (in Fig. 4 an alarm concerning the turbidity has been triggered) along with the related logs.

The merging of treatment and ICT technologies described above, allows for the following key features that significantly improve the potential for sewer-mining uptake:

- Automated maintenance. This is crucial to minimize the amount of time technicians spend on each unit (and hence the operational cost).
- Remote operation. This will allow an operator to monitor multiple units centrally without having to waste man-hours in transportation for periodic or unscheduled visits to each unit.

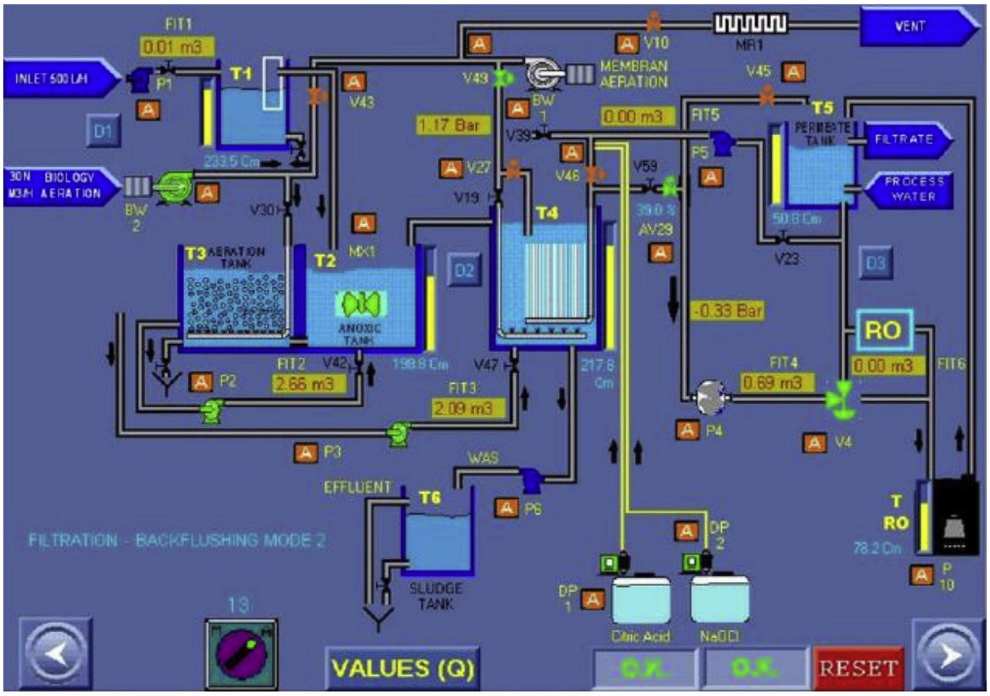

Fig. 3. PLC user interface main screen.

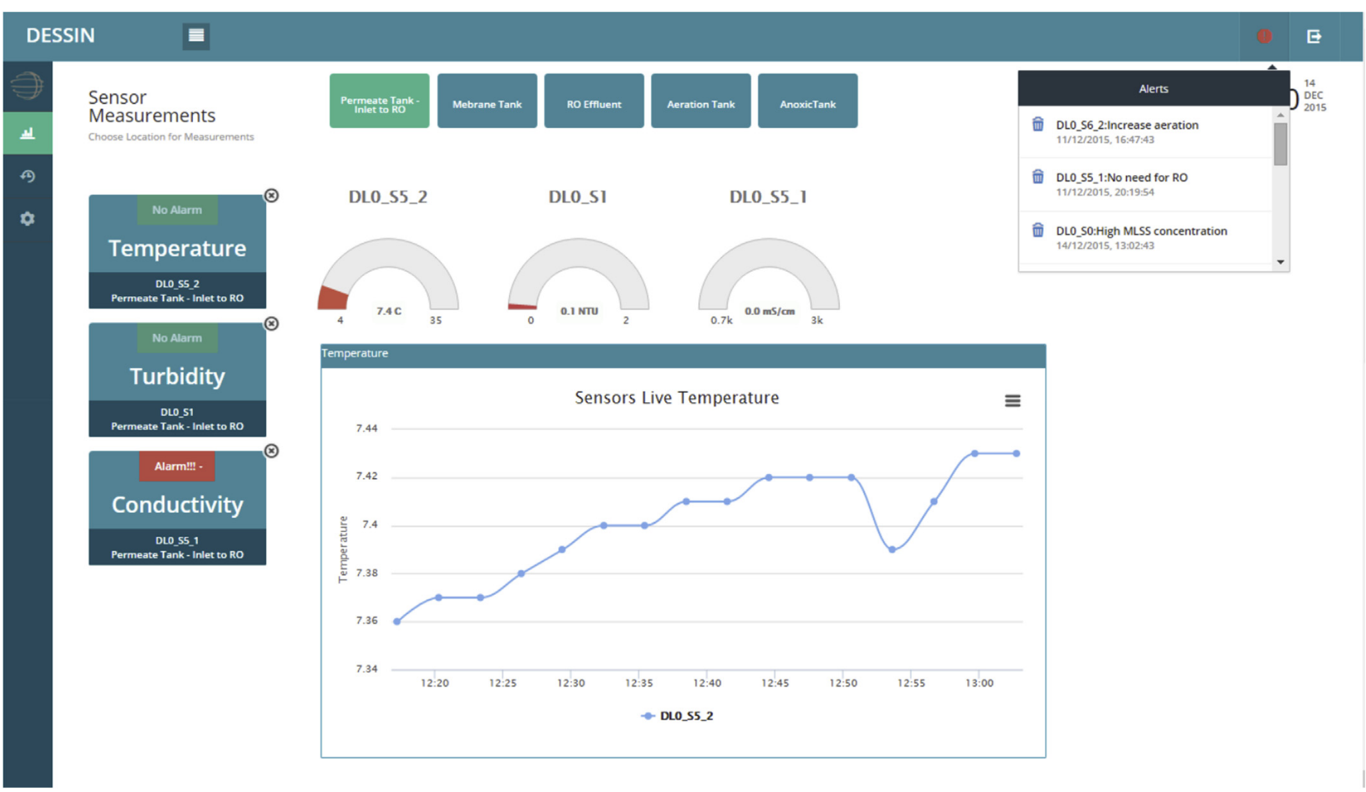

Fig. 4. Monitoring remotely the sewer-mining unit via web interface.

- Pre-fabrication. In order to minimize the cost and the time required to deploy a unit, the units should be pre-constructed and modular.
- Minimal weight and volume. It is evident that the smaller the units the easier the logistics. This is critical since some water needs may be seasonal and as such units should be easily stored, transferred and deployed at the installation location, and transferred back to storage. An additional benefit is that smaller units tend to cause less public disturbance (olfactory or visual).

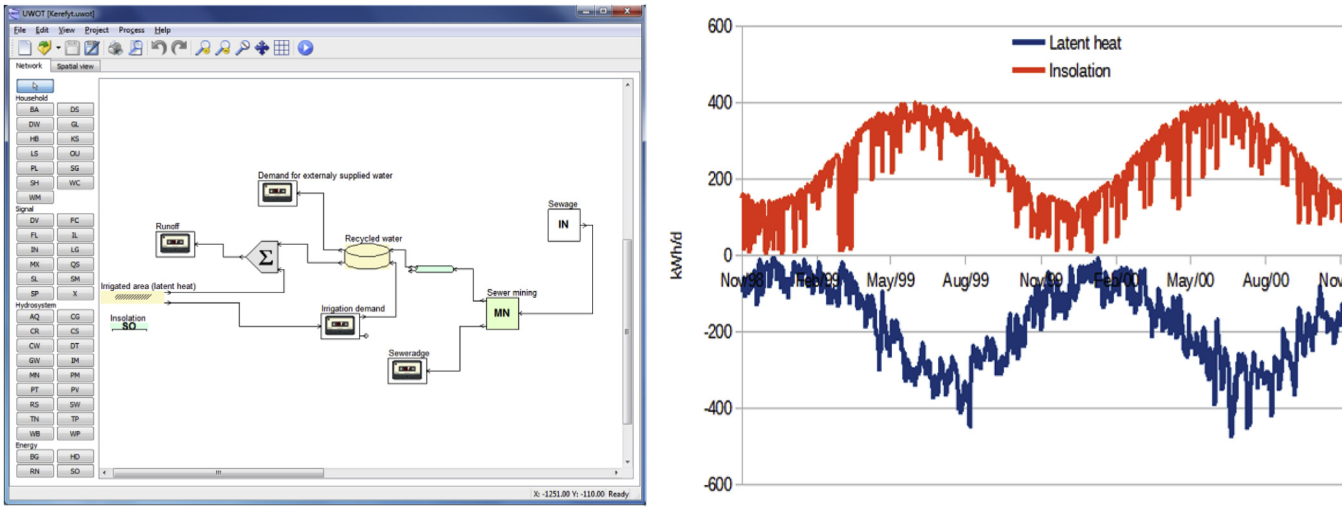

Fig. 5. Modelling water recycle with UWOT (left); insolation and latent heat (right).

2.3. Modelling tools

To facilitate and support the uptake of sewer-mining, two tools were developed, one for the local and one for the city scale. Both are briefly discussed in following paragraphs.

The tool for the local scale is based on UWOT (Makropoulos et al., 2008; Rozos et al., 2013). UWOT is capable of simulating all urban water cycle flows, one quality index (it can be BOD_5, dissolved oxygen, TSS or any other index selected by the user) and the energy related directly and indirectly with the urban water cycle. UWOT is employing a demand-oriented representation of the network in which demand signals instead of flows are simulated. The model distinguishes between two types of demand signals, the push and the pull signals. Push signals are related with a need to dispose an amount of water (e.g. stormwater, wastewater). Pull signals represent a need for an amount of water to cover a demand (e.g. irrigation). In the UWOT schematic representation of a network, pull signals have opposite direction to the resulting water flow (e.g. in left panel of Fig. 5 a water demand signal is emitted from the irrigated area and received, after passing through a signal logger, by the local tank, which results in a flow from tank to the irrigated area). Push signals have the same direction with the resulting flow (e.g. in left panel of Fig. 5 the tank overflow when the tank is full and the abstraction from mains when tank gets empty).

Fig. 5 (left panel) displays the network of the KEREFYT pilot unit as it is represented in UWOT. This representation includes one component that simulates the sewer-mining unit, one component for the recycled-water tank, one component that simulates the irrigation needs and the latent heat, and one component that simulates the insolation. According to the simulation, the amount of recycled water suffices to irrigate the area of 50 m^2 without requiring additional potable water (actually the maximum demand is 450 L/d, therefore a much larger area could be irrigated with the recycled water). The simulated latent heat and insolation are displayed in Fig. 5 (right panel). These timeseries can be used to estimate the sensible heat, which is responsible for the urban heat island effect (Rozos et al., 2016). Finally, UWOT simulates the quality of the wastewater in the pipe (the pipe from which wastewater is pumped into the unit) after the mix with the sludge from the unit. The following table gives the values of BOD_5 after the mix for various pipe flows and assuming BOD_5 before mix equal to 154 mg/L (Table 4). For the Monte-Carlo simulations employed by the spatial-stochastic tool (see the city-scale tool further down), an interpolation method is used to produce an arbitrary number of flow-BOD_5 pairs of values based on the following table.

Table 4
BOD_5 values (after mix) for various pipe flows.

Pipe flow (L/d)	BOD_5 after mix (mg/L)
10204	156
3401	176
340	377
102	896

In conclusion, UWOT can be used to estimate water needs, to properly dimension the capacity of the equipment required to supply with recycled water (permeate tank, treatment unit, pumps, etc.), to estimate the influence of the sewer-mining sludge disposal on the sewage quality (adverse effects due increase of wastewater strength) and to estimate ecosystem services (decrease of local temperatures due to evapotranspiration).

The modelling above assumes that wastewater is a non-limiting resource. However, in reality, sewer-mining decreases the wastewater flowing through a given sewer increasing at the same time its strength (since an amount of water is extracted from the sewage to cover local needs) while treatment by-products (sludge) with high BOD_5 loads are sent back into the sewer. High strength wastewater can cause sewer problems such as blockage, odour and corrosion (Marleni et al., 2012). To minimize the risk of adverse effects due to an installation of a sewer-mining unit, a spatial-stochastic tool was developed that evaluates alternative locations for installing such a unit, and assigns to them a score regarding their value (area served) and potential risk of sewerage corrosion.

To estimate the risk associated with each location, the dimensionless metric Z, originally proposed by Bielecki and Schremmer (1987) and Pomeroy (1990), is employed in order to quantify the probability of H_2S build-up. For a mapping between values of Z and corresponding characteristic pipe conditions the interested reader is referred to the relevant table in Pomeroy (1990). The metric requires information regarding sewage network characteristics and condition. More specifically the metric Z is defined as follows,

$$Z_i = \frac{0.3 \times 1.07^{T-20} \times [BOD_5]_i}{J_i^{0.5} \times Q_i^{1/3}} \times \frac{P_i}{b_i}, \quad (1)$$

where, i is the pipe index, J_i is the pipe slope, T is the sewage temperature, Q_i is the discharge (m^3/s), P_i is the wetted perimeter of the pipe wall and b_i the surface width of the stream. Eq. (1) can be used for a single pipe, thus we used a modified version of index Z of Pomeroy for a "chain"of pipes n:

$$MZ_c = \sum_{i=1}^{n} a_i \times Z_i, \tag{2}$$

where, a_i are weight coefficients. In this study we use weight values proportional to pipe length using the following formula, $a_i = L_i/L_{tot}$, where, L_i is the length of pipe i, and L_{tot} is the total length of pipes of chain ($i = 1, \ldots, n$). It is worth mentioning that literature includes a variety of metrics (Boon, 1995; Hvitved-Jacobsen et al., 2013; Lahav et al., 2006; Marleni et al., 2015), other than Pomeroys'Z that could be used to quantify the exact amount of H_2S in terms of mg/L.

A Monte-Carlo simulation, whereby the network operation is simulated multiple times with each simulation having different parameter values for wastewater discharge, BOD_5 loading and diurnal peak factors, gives, for each alternative installation location, the probability of the value of the metric Z to exceed a critical threshold (here $Z > 7500$ following Pomeroy (1990)) at any pipe downstream the sewer-mining unit. It is remarked, that the setup of the Monte-Carlo procedure is subject to expert judgment and the available computational tools and metrics. For example, in the case of metric Z one can consider as uncertain parameters all those related with its inputs, e.g., Q_i is affected by seasonal or diurnal peak factors; which in turn can be used within a Monte-Carlo simulation in order to account for their variability.

An example application of this methodology (Tsoukalas et al., 2016) with results from the city of Kalyvia Thorikou, in Greece, is displayed in Fig. 6. In the left panel, the sewerage topology and the green areas (potential recycled-water users) of the studied area are displayed. The red line is the unique downstream pathway from a node (i.e. a potential sewer-mining location) to the end of pipe wastewater treatment plant. The right panel displays the results of the Monte-Carlo simulation. The horizontal axis of this plot gives the expected value of the Z metric for all pipes downstream of the (potential) sewer-mining installation node. The vertical axis gives the maximum green area that can be served by each installation node. Results indicate that the node with ID 3 is a promising place to install a sewer-mining unit because it offers access to a large green area (the second largest) while also having a low (the second lowest) expected Z value and hence a low risk of H_2S build-up. In contrast, node ID 22, for example, although close to a green area of a similar size to that of ID 3, is less attractive due to the (much) higher associated risk of H_2S build-up.

Another illustrative example from the same case study is given in Fig. 7, where the top panel shows the expected Z values across the optimal path identified in the previous step for node with ID 3. Similarly, in the lower panel the probability of non-exceeding a threshold value (i.e., Z non-exceeding 7500) is calculated for the cross-section of the optimal path. Using such an analysis it is possible to identify critical pipes that could potentially lead to network problems. In this case, it is evident that the pipes with ID C171, C170, C169 and C168 are the most vulnerable since they are showing high values of expected Z and low probabilities of non-exceedance of the specified threshold value. This means that even in the optimal case of locating a unit in the node with ID 3, monitoring of the situation in these potentially vulnerable downstream pipes needs to be included in the regular post-installation maintenance and inspection operations (for example as an obligation of the unit operator towards the water utility that owns the network).

3. Case study

The unit described above was installed (Fig. 8) in a facility within the premises of the Athens Water Supply and Sewerage Company (EYDAP). The facility, which is called KEREYFT is EYDAP's sanitary engineering research and development centre and the unit was installed for the purposes of the EU research project DESSIN.

The effluent of this unit is used for the irrigation of an area of 50 m^2. At the time this paper was written, the unit had been running for 8 months. During this period, the following aspects where assessed: i) the challenges regarding operation of such a "Lilliputian" unit including the stability of the biological procedures, the identification of the unit optimal operation, and maintenance; ii) the quality of the effluent; iii) the reliability of the measurements provided by the online system.

The compact treatment unit performed quite satisfactory in all assessed aspects (Plevri et al., 2016a). The biological reactor of the MBR module proved very stable despite its small size. The maintenance procedure was easily performed as it was completely controlled via the PLC user interface. The electromechanical components operated flawlessly. The measurements obtained by the online system were verified against laboratory results and proved to be quite reliable. The only problems noticed were with the sensor controllers, which required (manual) reset after main power

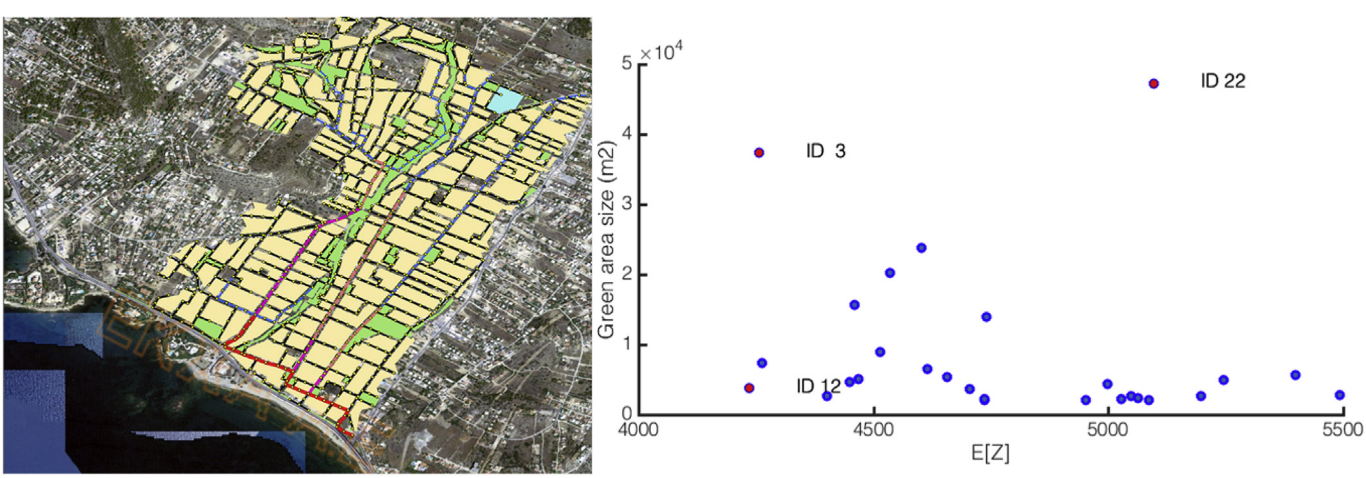

Fig. 6. Urban area with alternative locations of sewer-mining installation (left panel), evaluation of alternative locations with Monte-Carlo simulation (right panel).

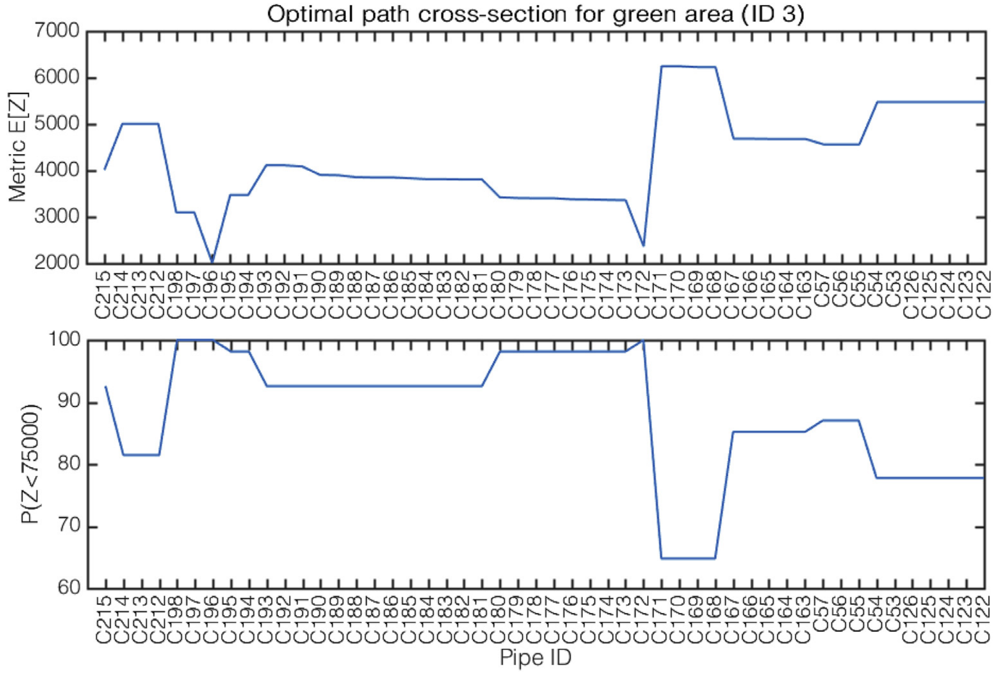

Fig. 7. Illustration of expected *Z* value (top panel) and probability of non-exceedance a threshold value (lower panel) across the identified optimal path of node with ID 3.

Fig. 8. Compact unit (left panel), irrigated area at KEREFYT (right panel).

failures. Another issue originated from the small PLC memory, which was getting frequently full with logged data. To resolve these issues an uninterrupted power supply unit was installed for the sensitive electronic devices, and a data logger was connected to the PLC to download data frequently and free the PLC memory.

The satisfactory results obtained from this pilot application enhance confidence into the ability of the unit to be used as a viable source of recycled water for (non-potable) urban applications. The unit initiated without a biomass inoculation and the start-up period lasted five weeks, in which the necessary conditions were met for biomass development and nitrification-denitrification processes started taking place. From the first results, it was evident that the MBR subunit could reduce the concentration of most pollutants under the recommended limits for water reuse (Plevri et al., 2016b). Despite the fact that the inlet showed significant fluctuations in several qualitative variables, the MBR's permeate characteristics remained steady. The RO treatment further improved the treated water quality, especially the aesthetical and microbial quantities. In general, the reclaimed water could fully meet the recycled water limits, as specified in the Greek national legal framework and specifically article 6 of the JMD145116/2011. In Table 5, certain critical qualitative variables referring to the effluent of both MBR and RO of the pilot unit are compared to the respective limits of the Greek legislation.

Focusing on the MBR permeate, the average COD was only 23 mg/L with a very high removal, averaging around 95% (Fig. 9c), while BOD_5 was always below 2 mg/L. The nitrification process was complete, with ammoniacal nitrogen concentrations reaching zero (Fig. 9d). Moreover, the removal of suspended solids was total, being always below the limit of detection of the analytical method (Fig. 9a). Looking at Fig. 9b, 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 had a certain stability. Finally, the trans-membrane pressure (TMP) value was constant, indicating that the membrane remained intact, without evident fouling. This proves that the two methods chosen for maintenance, back-flushing and

Table 5
Overall performance of the MBR-RO pilot unit (JMD 145116, 2011).

Parameters	Mean value (standard deviation)		Legislation limits
	MBR effluent	RO effluent	
TSS (mg/L)	<2	<2	≤2
VSS (mg/L)	<2	<2	–
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/100 ml)	307 (393)	ND	≤2
Faecal Coliform (cfu/100 ml)	1,09 (1,86)	ND	–
E.Coli (cfu/100 ml)	0,82 (0,98)	ND	≤5

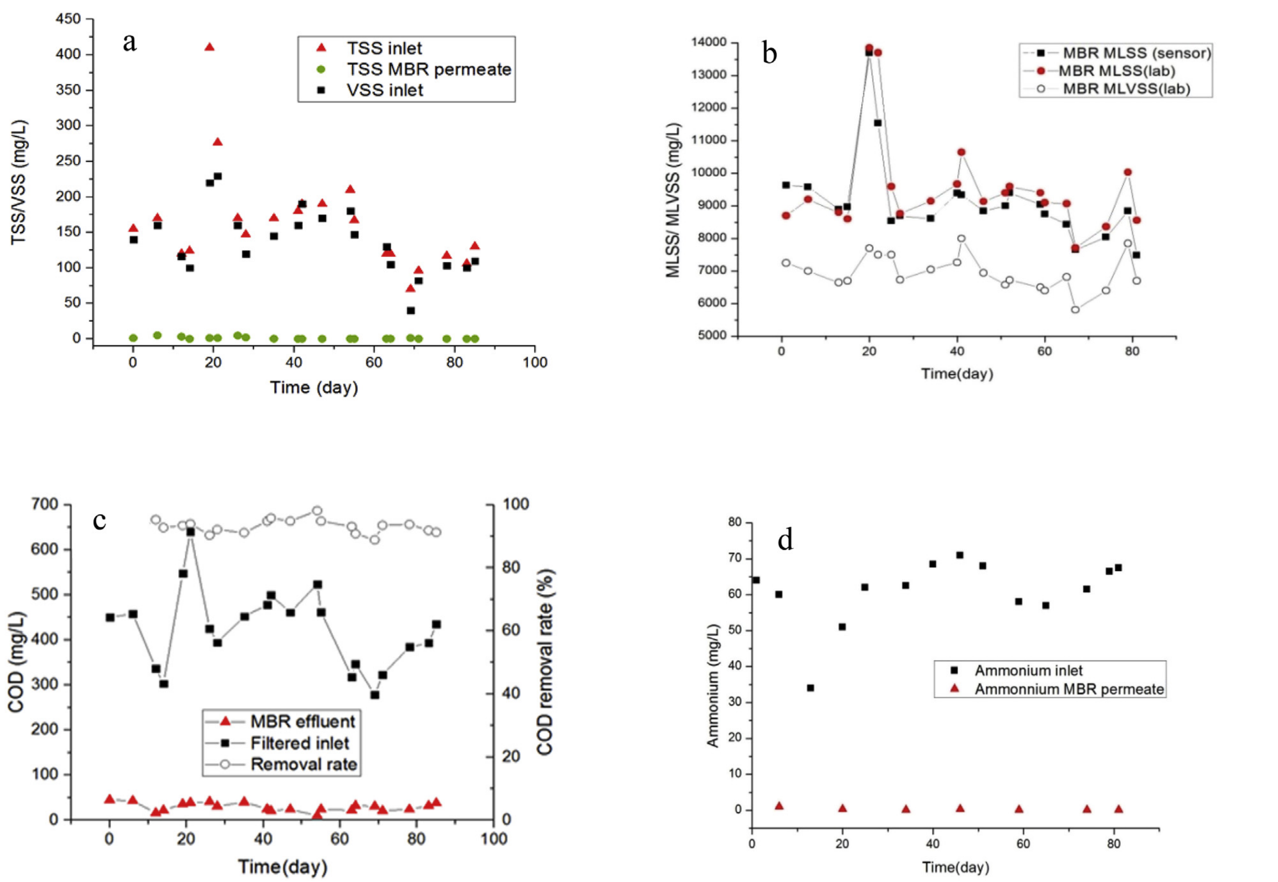

Fig. 9. MBR performance in (a) TSS, (b) MLSS, (c) COD and (d) Ammonium.

maintenance cleaning, were successful in maintaining the integrity of the membrane and recovery cleaning was not necessary.

The stability of the permeate armored the operation of the Reverse Osmosis, verifying that the MBR system is an ideal pre-treatment to RO. In the RO effluent, all microbial pollutants remained 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 were less than a quarter of the RO inlet. Other parameters than remained under the detection limit are COD and Total Phosphorus. Last but not least is the fact that conductivity, which remained unaffected by the MBR, was drastically reduced by the reverse osmosis. The rejection rate of the RO membrane, in terms of conductivity, averaged at values over 90% (Fig. 10).

3.1. Discussion: challenges for sewer-mining uptake

The challenges met and the issues highlighted by the pilot application concern: engineering, operational, regulatory, social and financial/business model issues:

3.1.1. Engineering challenges

Engineering challenges arise mainly from the following issues:

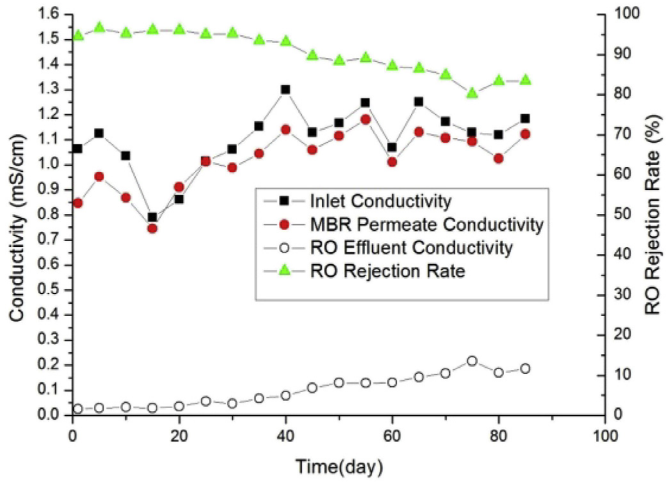

Fig. 10. Conductivity data retrieved by the installed sensors.

- from the requirements for a minimal unit footprint, in an effort to maximize deployability (even within small urban green spaces) and minimize community objections. As suggested by Xie et al. (2013), a major technical challenge is the development of a treatment process that can produce high quality treated water from raw sewage and is sufficiently simple and robust for decentralized applications. This issue is, to an extent, addressed currently as several manufacturers of compact units do exist (PCS, 2016; WPL, 2016) that prepare pre-fabricated modular components that can handle a variety of influent flow rates and BOD_5 loadings to meet quality requirements. The pilot application described above serves as a proof of concept towards this argument.
- from the challenge of selecting a proper location for placing the unit itself. Since the process is bi-directional i.e., involves the extraction of wastewater and the re-injection of treatment residuals to the network, the location of the unit is of paramount importance. A poorly selected location could lead to insufficient operation of the unit itself and eventually influence the broader network. Within this work, we have developed/customised two tools to address this challenge: UWOT could help in assessing the compliance of a sewer-mining unit with relevant regulations. First UWOT would estimate the required amount of recycle water for covering a local need (hence the volume drained from the pipe), and then the flow and quality after the mix of sludge with the sewage. UWOT (capable of running with time steps from a second to annual) could run with a 10 min' time step and typical timeseries of flow to ensure compliance over a 24-h period (as required, for example, by Sydney Water regulations (Sydney Water (2013)). Furthermore, the Monte-Carlo-based methodology proposed by Tsoukalas et al. (2016) can be considered as a first step towards a holistic approach in identifying suitable locations for placing sewer-mining units while concurrently trying to minimize the risks associated with its implementation i.e., odour and corrosion related problems. This has the advantage of taking into account the spatial and hydraulic characteristics of the network while simultaneously accounts for the variability of wastewater flow.

3.1.2. Operational challenges

The improvement of the *modus operandi* employed to run and maintain the unit is actually one of the largest challenge. The business model suggested here (based on SMEs) requires multiple units to be run and maintained across a large urban area with limited trained personnel. To accomplish this the treatment unit should: a) include automated procedures to minimize the need for human intervention and b) allow remote monitoring and control. In terms of monitoring in particular, the National Guidelines for Water Recycling of Australia (EPHC, 2006) suggest that the agency that will operate the unit should monitor at least the quality of the recycled water, the compliance of the operation with the nominal system performance, the plumbing operation, and the effect of recycled water use on the receiving environment. To this effect, our pilot application demonstrates that new smart ICT technologies offer solutions to achieve these requirements and at the same time allow for the required automation and remote operation (for remotely intervening whenever necessary). It is also worth mentioning that recent developments in the field of artificial intelligence and machine learning could be employed in order to develop algorithms, methods and decision support systems that dynamically learn and adapt the operation of the unit depending on current conditions and/or requirements. Work on this front is in progress within the context of this research (e.g., Bishop, 2006; LeCun et al., 2015; Maier et al., 2014; Russell et al., 2003; Schmidhuber, 2015). For example, a significant challenge identified early in the pilot was the preservation of the smooth operation of the unit: the reclaimed water flux should be guaranteed, in order to comply with the needs of its non-potable uses. But to achieve this, the developed biomass needs to be preserved. Biomass is very fragile and thus vulnerable to abrupt changes in the unit's parameters. As such, the operator should always have a stack of spare electromechanical equipment that are vital to the biological processes taking place, such as blowers, and be ready to immediately replace failing parts.

3.1.3. Regulatory challenges

These arise from constraints posed by municipalities in terms of locating these units within the city area (e.g. need for environmental impact assessment etc.) and are very country specific. They also arise from constraints posed by water companies operating the sewerage system regarding (upper bounds of) the concentration of chemical and physical parameters in the disposal of wastewater into municipal sewers. For example, EYDAP performs spot-checks of non-domestic users' disposals in sewage network in order to determine compliance with the relevant legislative provisions which for EYDAP is: BOD_5 5 < 500 mg/L and TSS <3000 mg/L. Though these regulations are usually set to prohibit commercial/industrial disposal of high organic content wastewater into the wastewater network, they are restricting the opportunities related to sewer-mining. For this reason, modifications to existing regulations are required. A potential approach (already applied in some cities in Australia) would be to have regulations that take into account both the capacity of the treatment unit and the capacity of the receiving wastewater system. This requires setting upper limits (e.g. concentration of organic matter) and/or lower limits (e.g. flow) that are defined in the wastewater stream right after the mix of the sewage with the sludge from the sewer-mining unit. For example, Sydney Water (2013) requires that the concentration of suspended solids after the mix (measured by analysis of a composite sample over a typical 24-h period) should not exceed 600 mg/L.

3.1.4. Social challenges

The social factor, i.e., social acceptance of these practices, is a notoriously difficult factor to anticipate and manage. This is partly linked with public perception of recycled water which is perceived in a generally negative fashion. In a recent survey in Greece, Koutiva et al. (2016) found that this aversion reduces as the recycled water use moves away from the end users BOD_5 y. As such, and since the effluent easily meets stringent removal standards (Lutchmiah et al., 2011; Xie et al., 2013) it is suggested that for uses such as urban green irrigation (or equivalent commercial uses such as golf courts irrigation) public acceptance would be sufficiently high to allow for demonstrative units to be deployed as a first step towards building trust. Another public concern refers to malodours coming from the treatment unit. Experience from the pilot application in Athens suggest that no unpleasant odour was noticed even when standing next to the treatment unit. However, the pilot unit capacity was only 10 m^3/d. A sewer-mining unit with much larger capacity would be perhaps less delicate. Even so, no serious problem is expected at a distance of a few tens of meters from the unit, which in any case would be a restricted area. Last but not least, research also suggest (Castro et al., 2011) that beyond striving to minimise the negative impacts of an intervention, it is important to also quantify the positive benefits of the intervention in the form of (ecosystem) services. Ecosystem services linked to the sewer-mining unit, including but not restricted to heat island effect reduction, especially in water scarce areas (Rozos et al., 2016), such as the ones calculated by UWOT, could play an important role in changing public perception and developing a more positive image for reuse in general and sewer-mining in particular. This is especially true in water scarce environments, such as Southern Europe and the Mediterranean where extracting more water from regular sources to irrigate urban green spaces, and thereby improving wellbeing for city dwellers during the hot summer months is not an option.

3.1.5. Business model challenges

As the potential benefits of sewer-mining for the circular economy and ecosystems are easily identified, a major issue —with significant social extensions-concerns the establishment of a *functional* business model that will ensure social acceptance and economic profitability for the operator. Empirically, models that aim at providing high value-added services with absence of *subsidization* or excessive *bank lending* at every stage of the commercial application (initial, intermediate or mature) prove to be the most resilient in time (Albach et al., 2014, p. 158). In relation to the features of small-scale applications —such as the pilot study area-two business models comprise the main candidates for sewer-mining technology commercialization: **(a)** full provision of the service by the water utility (in this case EYDAP) who owns the sewerage networks or **(b)** privatization of the service (e.g. by an SME), while the water utility maintains the property of the networks and receives a rent for their use (e.g. a constant monthly fee or a fee proportional to the demand for the network's use). This second business model is a type of *public-private partnership* (PPP), a highly common practice for new water infrastructures under formation (Marin, 2009). The PPP model differs from the public supply model in the sense that all *business risks* and *benefits* are —by contract-ceded to the private counterparty. In this context, the decision between the two business models is a matter of the ratio between the *marginal benefits* and the *marginal costs* from the technology's application. Generally, the higher this ratio is, the higher is the potential for private interest and involvement.

A primary estimation on the unit's cost has been undertaken by Plevri et al. (2016b). They suggest costs ranging from 0.86 euros/m^3 for the MBR-UV scheme to 1.07 euros/m^3 for the MBR-UV-RO scheme, which should be considered a satisfactory starting point for the sewer mining technology's diffusion, even for conventional pricing methodologies. It is, however, further suggested that under ‘full cost’ methods (where both economic and environmental costs are accounted for), the sewer mining technology is expected to become significantly more attractive, while a large part of its cost reduction rate depends on ‘learning curve’ attributes. In particular, assuming that for small-scale applications the marginal costs between the private and the public sector do not vary significantly, the business model selection depends on the accurate valuation (and pricing) of the marginal benefits - mainly those deriving from *water-enhanced ecosystem services*. A general framework for quantifying the benefits of ecosystem services in macroeconomic accounts has been proposed by the UN (2014a,b). Water-enhanced ecosystem services concern *the functions of the (local) ecosystem that used to be inactive due to the limitations in available water*. For example, in the study area, the most notable derived service is microclimate regulation from watering local parks. This provides the community with *direct, local and collective benefits* from less energy use for heating and cooling during the year, features that are expected to promote the technology's social acceptance. Other, more entrepreneurship-oriented ecosystem services, may come from the realisation of (formerly non-viable) projects, such as touristic activities, urban farming, hydroponics and other environmentally based activities, including education. These benefits could be multiplied —both qualitatively and quantitatively-in a potential up scaling of the sewer mining technology, triggering an economic shift towards new technical specialisations and jobs related to urban water recycling. However, at this point a quantitative estimation of this trend would exceed the scope of this work. What should be noted is that at the small-scale it is the *variety* of ecosystem services that matters most rather than their *scale*. Hence, from a business point of view, the achievement of *economies of scope* (diversification of ecosystem services) is more important from *economies of scale*; the latter being a more appropriate target for large-scale urban webs or *industrial ecology* complexes (Ehrenfeld and Gertler 1997). At the small-scale, the conditions for the organization of local and transparent water-enhanced ecosystem service markets between few competitive end-users are more favourable. In such markets, a private operator (e.g. a start-up or an SME) would seem more flexible to manage the challenges of ecosystem services diversification.

4. Conclusions

It is argued that sewer-mining could become a major ‘game changer’ in the increase of wastewater reuse within the (ever increasing) urban environment. Sewer-mining units, integrating advanced compact treatment technologies with ICT offer a series of benefits and present an opportunity for more SMEs to enter the European (and Global) water market, not only as technology providers but also as operators and service providers. Such SMEs will be able to provide water to cover non-potable demands (e.g. irrigation, cooling towers, car washing, etc.) by deploying compact sewer-mining units at the location of demand.

To support this argument, a pilot sewer-mining unit was set-up in Athens and its main characteristics were described. To facilitate planning regarding sewer-mining applications, two tools were developed. The first tool, UWOT, helps to estimate the non-potable water demand, the consumed energy, the sewage quality after the sewer-mining sludge disposal and the benefits from ecosystem services. The second tool helps in larger scale planning to locate the most suitable locations for installing sewer-mining units by taking into account the maximization of serviced area and the minimization of potential corrosion of the existing sewerage network.

A series of challenges for a large-scale uptake of sewer-mining were also briefly presented and discussed. Although these challenges are far from being met, it is argued that none of them are insurmountable and that the present social, financial and engineering context is in fact favourable towards resolving them.

Consequently, we conclude that sewer-mining provides a real opportunity that can help European societies to comply with the requirements of directives (e.g. the WFD alleviating pressure on water bodies from increased abstractions), increase ecosystem services even in water scarce areas (like the European South and the Mediterranean) and to progress towards achieving some of the most advanced ambitions of the European Commission (e.g. the Junker Commission's drive towards Circular and Green Economies) while, importantly, encourage the private sector to make investments in technology intensive, socially beneficial and environmentally friendly areas achieving triple bottom line aspirations.

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