Regional Environmental Change
https://doi.org/10.1007/s10113-018-1292-z

REVIEW

The reuse of reclaimed water for irrigation around the Mediterranean Rim: a step towards a more virtuous cycle?

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Received: 25 November 2016 / Accepted: 23 January 2018

Abstract
Climate change and a growing population around the Mediterranean Rim are increasing the need for water and, consequently, the pressure on resources in terms of both quantity and quality. High-quality water should be primarily reserved to drinking water while reclaimed water is an alternative for other usages. A review of situations in Tunisia, Jordan, France, and Italy involving the use of reclaimed water highlights the disparity in national regulations governing this alternative water resource and in its management. On the first hand, the use of recycled water for irrigation can have an adverse impact on public health and the environment, depending on treatment and irrigation practices. On the other hand, it may also represent a new source of water: wastewater should no longer be considered as waste but, rather, as a new resource to be handled in a circular economy-type loop. Current scientific knowledge in agronomic and environmental sciences, as well as in the economic and social sciences, can be integrated and used to lower the associated risk through the effective management of irrigation using recycled water and to address the following questions: (i) How can the time-varying nutrient needs of crops be managed to operate safe environmental reuse within an adapted risk assessment framework? (ii) What socio-economic models can render this integrated approach sustainable? (iii) What treatment systems and irrigation technology can be used to support these ideas and with what information? (iv) What changes in the regulations are needed?

Keywords Wastewater reuse · Irrigation in agriculture · Environmental impacts · Sanitary and environmental impacts · Systemic approach · Integrated treatment systems

Introduction

The Mediterranean region is particularly exposed to the consequences of various changes: climate, reduction in biodiversity, global warming, and population growth. This means increased pressure by human societies on renewable but limited natural resources, notably surface water, along with an increased need for food (mostly from irrigated areas) and drinking water. According to the International Water Management Institute (IWMI), by 2025, 1.8 billion people will live in countries or regions suffering from absolute water scarcity, which means water availability below 100 m^3/inhabitant/year. Today, most countries in the Middle East and North Africa can be classified as facing absolute water scarcity (IWMI 1998), thus creating a very strong pressure on water resources as well as a competition for water between the various end users. Mediterranean societies are among the most vulnerable to the effects of climate change due to the increasing degradation of their water resources (overuse, pollution, salinization, etc.) and increasing water demand in agriculture as well as in the urban, industry, and energy sectors. Agriculture is the largest water user. The 2017 UN-World Water and Development Report (UNWWDR 2017), based on FAO-Aquastat data,[1] states that the water consumption for crop irrigation amounts to 70%, on average, of the world water requirements that locally could reach 90% of resources. On the 30% remaining that is used by cities and industry, about 6% is consumed and the rest discharged into the environment, of which only 5% is considered treated; the remaining 19% is discharged with little to no treatment. Thebo et al. (2017), through a GIS-based

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[1] http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=eng

analysis on the portions of river basins influenced by metropoles of more than half a million inhabitants, estimates that about 6 Mha are irrigated using controlled treated wastewater (TWW) and about 30 Mha with diluted or untreated WW. This roughly corresponds to 10% of the world irrigation surface area and to 277 km^3 of wastewater over the 864 km^3 (treated or not) disposed annually. The potential of WW reuse, and the fact it could easily serve to replace good water quality resources, is increasingly recognized, provided management (volume and nutrients) and pollution issues are addressed.

To reduce the pressure on freshwater resources, and to preserve them for the provision of drinking water, it is urgent to rethink how these resources are managed and improve water use efficiency by combining better management and policy reforms. In this context, reclaimed water reuse has become common practice in many Mediterranean countries since the mid-twentieth century.[2] Here the term "reuse" means the use of wastewater, be it raw or partially treated, for beneficial purposes. It involves different sources of wastewater of variable quality, and the main, but not exclusive, wastewater application is irrigation. Many countries see water reuse as an important aspect of water resource management, mainly destined for irrigation purposes. In addition, the development of irrigated agriculture in rural areas as well as around—but also within—urban centers offers a new opportunity to consider the reuse of reclaimed water in enhancing the water supply for agriculture, and thus the improvement of food safety and security, as well as the reduction of poverty in rural communities (Jhansi and Mishra 2013; Lazarova et al. 2013; Kihila et al. 2014). Countries such as Israel, where about 75% of reclaimed water is reused, and Tunisia, where about 25% of reclaimed water is reused, have become real "champions" of the practice (Kellis et al. 2013; Nasr Abroug 2014). In the USA, about 7% of reclaimed water is reused, and represents 29 and 11% of reclaimed water in California and Florida respectively. Millions of hectares of cropland are irrigated with sewage effluent in China, India, Mexico, and Mediterranean Rim, in many cases without adequate treatment (Lazrova and Bahri 2005; Jimenez and Asano 2008; Thebo et al. 2017). For this reason, the choice of appropriate and cost-effective wastewater treatments, and the adoption of suitable irrigation practices are the two major undertakings necessary to protect public health and prevent adverse conditions and damage to crops, soils, and groundwater. In fact, the use of wastewater for agricultural purposes can pose significant risks to farmers and, more generally, to public health. There are many risk factors associated with the reuse of water for vegetable irrigations purposes. Other risk factors, such as soil salinization or the accumulation of toxic chemicals, have harmful effects that are only measurable over longer periods, and these risks increase with the continuous use of wastewater (Kukul et al. 2007) be it controlled (reclaimed) or not (raw). The quality of irrigation water has been shown to potentially affect soils, crops, food quality, safety (Khan et al. 2008), groundwater, the management of water (Batarseh et al. 2011), and populations exposed to the irrigation water (farmers, consumers, etc.). In fact, one of the main problems is that there are no common regulations, even at the European level.

Despite the well-recognized uses of TWW around the Mediterranean Rim, scientific knowledge on the topic needs to be improved, and the analysis of practical experience using recycled water for irrigation needs to be increased in order to lower the associated risks and to implement effective management practices. The first objective of this article is to provide a review of a number of situations in different Mediterranean countries involving the reuse of TWW in irrigation in terms of their respective treatment and irrigation practices. From these reviews of specific situations, the second objective is to identify different scientific issues related to water reuse in irrigation and to analyze them with respect to agronomic, environmental, and technological aspects. In particular, we promote here an integrated approach in which wastewater is viewed as a new resource to be treated in order to match the demand for water, while also taking into account the constraints related to its health and environmental impacts. Such an approach requires a shift from a vision in which wastewater is treated in WasteWater Treatment Plants (WWTP) to another one in which wastewater is considered as a raw material to be processed in Waste Resource Recovery Facilities (WRRF), thus replacing the classic WWTP (see Online Resource 1). Finally, to assess the technical benefits of WRRF, and, in more general terms, of a comprehensive and integrated approach to water management including the use of reclaimed water, a sustainability approach integrating environmental and economic as well as social considerations is presented.

Overview of water reuse practices and state of the art in four countries representative of the situation around the Mediterranean Rim

In the following, we have compiled the main points regarding reuse in four Mediterranean countries (Italy, Jordan, France, and Tunisia)—both from a practical perspective and from a number of environmental and human sciences viewpoints—to highlight the diversity of experiences and bottlenecks. For Italy, Jordan, France, and Tunisia, respectively, these experiences are described in four parts: (a) Elements of Context and Figures, (b) Treatment and Irrigation Technology, (c) Agriculture, Soils, and Groundwater Levels, (d) Regulation and Socio-economic aspects.

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[2] This practice refers to the use of non-conventional waters.

Italian experience

1. A survey of Italian treatment plants estimated the total effluent flow (potentially available for reuse) at about 2400 Mm^3/year (TYPSA 2013). Nowadays, reclaimed water is used in Italy mainly for agricultural irrigation, covering over 4000 ha. Although there is no organized national network of "WW reusers," several case studies on the practical implementation of the reuse of TWW in Italy include relevant applications in both the north and south of the country. In regions like Emilia Romagna (WWTP of Reggio Emilia), Lombardia (WWTP of Milano-Nosedo), and Piemonte (WWTP of Torino), large volumes of treated effluent are currently produced and delivered to local users. In southern regions such as Puglia and Sicily, a number of pilot-scale projects and actual applications have been carried out that are specifically aimed at compensating for the lack of natural resources typical of Mediterranean areas (Lopez et al. 2006; Lonigro et al. 2015).
2. The controlled reuse of municipal wastewater in agriculture has not yet been developed in many Italian regions. Compliance with new Italian standards requires advanced treatment, entailing consequences on the economic viability of reclamation. Another negative aspect is the plethora of parameters to be monitored—more than 50 items—that often require high measurement frequencies. Furthermore, no regulatory distinction has been made between the different crops to be irrigated with reclaimed wastewater (restricted/unrestricted irrigation) and no attention has been paid to the influence of different irrigation options in reducing sanitary risks (e.g., subsurface, drip, or sprinkle irrigation).
3. In coastal areas, treated-wastewater reuse is recognized as a possible tool to mitigate groundwater salinization caused by overexploitation of underground water resources and consequent seawater intrusion. However, injection of treated effluents into deep aquifers is forbidden in Italy; therefore groundwater recharge can only be achieved through surface spreading and infiltration systems.
4. Water reuse for irrigation in Italy has been regulated since 1977 by the Water Protection Act (CITAI), but a new set of regulations was promulgated in 2003 (Decree of the Ministry of Environment 185 2003), applicable to agriculture, non-potable urban, and industrial water reuse. A rather restrictive approach was adopted such that many quality standards for reclaimed water are the same as for drinking water. The relevance of nutrient recovery, and the advisability of adopting standards and technologies tailored to the different reuse applications, have been highlighted as important findings of the recent pilot experiments (Vergine et al. 2015, 2016).

Jordanian experience

1. The scarcity of water in Jordan, which has always already attained one of the highest four levels of water poverty worldwide, has motivated governmental and non-governmental efforts to promote the reuse of treated wastewater as an additional water resource. By 2017, more than 30 WWTPs were already operating all over the country that has an area of 89,341 km^2 with a total population of 9,531,712 (MWI 2016). Safe sanitation is provided for more than 93% of the population of which 63% avail of sewer and treatment systems. The latter percentage is expected to increase to 80% by 2030. Almost 91% of the TWW is reused in agriculture and this water contributes 17% (175 Mm^3) to the annual water budget that is currently 1027 Mm^3. The TWW covers approximately 25% of the irrigation needs, which is estimated to be 700 Mm^3 and around 60% of the annual water budget. The TWW (up to 30%) is primarily used to irrigate the cultivated areas at the premises and vicinities of the WWTPs and is regulated by agreements signed with farmers and other official entities. The remaining TWW flows down wadis and reaches downstream water bodies such as dams. The biggest WWTPs (Khirbet As Samra, Jerash, Baq'a) release more than 70% of the total Jordanian TWW to the King Talal Reservoir (KTR) where it mixes with the annual rainfalls. The farmers in the middle-south Jordan Valley, where most irrigated agriculture occurs, rely on the KTR dam as they do not receive any other surface water. This dam plays, therefore, a crucial role for agriculture in Jordan Valley. The TWW is only used for irrigation of non-edible crops like forage crops, and for nurseries and trees (MWI 2016).
2. The most commonly used WW treatment technologies are activated sludge systems and, to a lesser extent, trickling filters and extended aeration. Most WWTPs are carefully designed and operated to produce effluent compliant with Jordanian reclaimed water standards. In addition, any potential pathogen-based contamination is very limited due to the natural purification that occurs while TWW is transported along wadis and into the reservoirs till the point of use. However, the TWW with high salt content is an issue that needs to be addressed at WWTPs that receive a share of industrial WW and brine from desalination. Farmers mainly use mulch (plastic cover on soil) and drip irrigation to avoid excessive evaporation and effectively enhance the microbiological quality of the crops as well as prevent microbiological contamination. The locations where pure TWW obtained directly from the WWPTs, such as Wadi Musa, also apply drip irrigation, but the TWW can only be used for the cultivation of forage crops. Agriculture will be allowed to expand in Jordan, but only if additional TWW becomes available (MWI 2016).

3. The use of treated wastewater has significantly reduced pressure on the endangered renewable freshwater sources. The ongoing shift towards sewer systems, wastewater treatment, and reuse has diminished the prospect of soil and groundwater contamination that was previously a threat due to the widespread use of household septic pits. Although the Jordanian WWTPs do not produce significant amounts of sewage sludge, it is of high quality and can be used as a soil conditioner or fertilizer. However, any beneficial use of this sludge will only be made possible in the near future if effective legislation on sludge reuse comes into force.
4. Several sets of standards and guidelines for wastewater, sludge, soil, and crops were established by various organizations such as the Water Authority of Jordan and the Ministry of Water and Irrigation. In addition, the Jordanian Policies and Laws governing TWW are enhanced year after year and are aimed at promoting higher TWW quantities of ever improving quality (MWI 2016). Jordan has made also great advances in wastewater collection and, in order to advance further, the country has embarked on a strategy aimed at rural communities, and not only major population centers. The national framework for decentralized wastewater management was built to achieve the UN Sustainable Development Goal, i.e., providing "access to water and sanitation for all." To achieve this, the framework provides the regulatory, managerial, and technical foundations for implementing a decentralized approach to wastewater management in Jordan. This approach consists in extending wastewater services to rural communities, enhancing the potential of freshwater substitution, and improving sanitation and public health (MWI 2015). A National Water Reuse Coordination Committee (NWRCC) was formed in 2003 by the Ministry of Water and Irrigation. It is made up of, among others, the Secretary-General of Water Authority of Jordan, a representative from the Royal Court, the Secretary-General of the Ministry of the Environment, the Director General of NCARTT, and the Unit Director of the Ministry of Water and Irrigation. The NWRCC discusses all issues involving water reuse in order to enhance coordination and to avoid overlapping between ministries.

French experience

1. France only faces local and seasonal episodes of water resource deficits. Therefore, the reuse of wastewater is restricted to particular regions, and only about 40 TWW reuse projects have been identified, essentially for golf courses, turf production, and gardens or agricultural irrigation. The average daily volume of TWW reused in France was estimated at 19,200 m^3 (about 7 Mm^3 per year) in 2014 representing about 0.1% of the produced TWW and less than 0.3% of the total water used in irrigation. The most important agricultural projects are located in Clermont-Ferrand (center of France) and on the Noirmoutier Island (Western Oceanic France). In Clermont-Ferrand, 700 ha of seed maize, maize, beetroots, and wheat are irrigated with 0.9 Mm^3 of TWW per year. In Noirmoutier, 320 ha of labeled potatoes are irrigated with TWW representing an average yearly volume of 0.38 Mm^3. In the Mediterranean area, pilot irrigation projects have been implemented before an expected expansion to a broader scale. In Gruissan (Southern France), about 1 ha of vineyard is irrigated with TWW in order to characterize long-term impacts of pollutants on agricultural production and on the quantity and quality of the wine produced. Almost 20 golf courses are irrigated with TWW in France. Many are located on the Atlantic coast where the main driver to these projects is often the need to limit TWW discharge into the sea and the environment. Rhuys-Kerver golf course (in Brittany) reuses TWW. Discharges into sea bathing areas are therefore curtailed. The golf courses have access to a water resource that are available all year long, while water restrictions are often applied in summer on conventional water resources.
2. The relevant regulation was updated in 2014 to better account for the case of sprinkler irrigation techniques, and provides wind velocity limits at which irrigation should be stopped depending on the operating pressure in use, and also stipulates safety distances accounting for sprinkler maximum range. Many new water reuse projects are planned for the upcoming years. Future regulation proposals should include new water reuse options such as urban uses, firefighting, and wetlands.
3. In many cases, agricultural production has been extended and sustained thanks to TWW: high-value seed maize can be grown in Clermont-Ferrand and potato cultivation could be extended in summer in Noirmoutier, thus limiting the exploitation of potable water imported from the continent, while also mitigating pressure on existing natural resources and generating higher incomes for farmers and for the territories.
4. In the Mediterranean area, the Sainte-Maxime golf course is irrigated with TWW. This project has freed up conventional water for higher value urban uses. Cost-benefit[3] analyses have highlighted the benefits of water reuse for both Sainte-Maxime and Rhuys-Kerver projects. The use of TWW from WWTP for agricultural, turf production, and garden irrigation purposes is regulated since 2010. Prior to 2010, water reuse regulation was not clear and few projects had emerged. The 2010 regulation

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[3] Abbreviated as CBA (see Online Resource 2)

introduced quality standards for TWW based on four quality levels (from A—high quality—to D), cf. French Regulation 2010. The higher the risk of human exposure (valorization of the crops, type of irrigation), the higher the treatment level needed.

Tunisian experience

1. Tunisia was among the first countries around the Mediterranean Rim to have established and implemented a water reuse policy in the 1980s with water reuse operations integrated into the planning and design of sanitation projects. Water reuse has become an integral part of overall environmental pollution control and water management strategy. It is viewed as a way to increase water resources, provide supplemental crop nutrients, and protect coastal areas, water resources, and sensitive receiving water bodies. The country has a long history of water reclamation and reuse for agricultural irrigation. Other applications in Tunisia include irrigation of golf courses, green belts, and hotel landscaping. Reclaimed water is also used for recharging groundwater. Since the mid-1960s, a step-by-step approach to expand reuse has been adopted. The strategy consists of (1) extending wastewater treatment to all urban areas, (2) conducting pilot- and demonstration-scale irrigation operations on agricultural and green areas, (3) establishing large-scale irrigation schemes, and (4) implementing a policy aimed at increasing the percentage of treated effluent for reuse. Currently, the National Sanitation Utility is running 110 WWTP treating annually 240 Mm^3 of wastewater (Nasr Abroug 2014). Only 57 Mm^3 of the total treated-wastewater volume (24%) are reused, 54% of which is destined for indirect uses such as wetlands and sebkhas, and the remaining 46% for direct applications such as irrigation of crops (32.8%), golf courses (12.5%), and green areas (0.9%). These 57 Mm^3 could irrigate up to 30,000 ha of cultivated areas whereas only 8256 ha have been equipped for reuse. By 2020, the area irrigated with reclaimed water should reach to 20,000–30,000 ha, i.e., 7–10% of the overall irrigated area.
2. Wastewater effluent is treated to secondary levels mostly using activated sludge processes (78%); the quality of treated wastewater shows high levels of COD, BOD, and phosphorus. In Tunisia, several research studies of real field conditions have been carried out regarding the physical-chemical and biological quality of reclaimed water and its impact on soils and plants. The results have shown the feasibility of water reuse provided some precautions are taken.
3. The concentrations of almost all regulated elements in raw and reclaimed water were below the maximum concentration recommended for agricultural reuse based on the Tunisian standards (INNORPI 1989) and had a high fertilizing content which, in the cases of nitrogen and potassium, may directly exceed plant growth requirements. The application of nitrogen that exceeds crop growth requirements may present some risks for crops and/or groundwater. The different treatment processes did not result in a complete removal of pathogenic bacteria such as salmonella, except for effluents from stabilization ponds which were free from such pathogens. Storage in ponds showed an improvement in the quality of reclaimed water. Investigations of the long-term effects in the La Soukra area, which has been irrigated for more than 20 years with reclaimed water, did not show any notable effects on soils, crops, or groundwater. A study conducted within this scheme to evaluate the impacts on health linked to reclaimed water reuse could not determine a clear cause-effect relationship between the observed diseases and the reuse practice. Another epidemiological study conducted within the Zaouiet Sousse scheme did not reveal any significant differences in the exposed and non-exposed populations.
4. Water reuse in agriculture is regulated by the 1975 Water Law and by the JORT Decree No. 891047 of 1989. The quality criteria for agricultural reuse of reclaimed water were developed using Ayers and Westcot (1985) and WHO (1989) guidelines on restricted irrigation (less than 1 nematode egg/l), along with other Tunisian standards related to irrigation or water supply. Regulations allow the use of secondary-treated effluent on all crops except vegetables, whether eaten raw or cooked. Therefore, depending on climate conditions, about 25–40% of reclaimed water is used to irrigate industrial and fodder crops, cereals, vineyards, citrus, and other fruit trees. Golf courses (Tunis, Hammamet, Sousse, Tabarka, Tozeur, and Monastir) and some hotel gardens in Jerba and Zarzis are also irrigated with reclaimed water. Regional agricultural departments supervise the enforcement of water reuse decrees and collect related charges. In order to promote water reuse, the reclaimed water charge was set at 0.018 €/m^3, which is below the tariff for conventional surface water used in other irrigation systems (0.026–0.092 €/m^3). However, farmers still prefer conventional water, even if it is more expensive (Ben Brahim-Neji et al. 2014).

These experiences highlight the following points. What is at first surprising is the differences in the proportions of wastewater reused in the four situations (between 0.1 and 25%, respectively for the French and Tunisian case). Such findings highlight that the main driver of national water management strategies is the level of water stress. While not dismissing the role of social aspects, the diversity of available data (quantitative and qualitative) in each of the four experiences reveals the diversity of applied regulations, of the perceived link between hazards and risks and the diversity of water stresses. Concerning regulations and standards, they state the levels of quality expected at treatment plant outlets while not considering the effective WW uses: they rely on strict norms without any consideration of the monitoring capacities available, or the harmful impacts related to some uses (like the effect of soil microbial ecosystems on pathogens, which form a "barrier" and limit their dissemination).

We discuss and suggest hereafter how regulations could be harmonized beyond the guidelines of FAO and WHO. With respect to risk management, the experiences attest to a primary focus on first-level hazards, e.g., those related to pathogens and pollutants, while little attention is given to the related long-term effects. In this paper, we discuss the problems related to the accumulation of some chemicals and their degradation sub-products, the salinization, and the contaminants of emerging concern. Regarding the treatment and distribution technologies, the experiences highlight reuse practices relying on technical chains which are designed to address treatment requirements only, and not resource recovery (water + nutrients). To this purpose, we discuss the recent evolution of sewage and wastewater treatment plants.

Issues related to wastewater applications around the Mediterranean Rim

Taking into account the different Mediterranean situations described above, different scientific issues need to be addressed along with a range of other agronomic, environmental, technological, and social questions in order to promote the sustainable reuse of TWW for irrigation.

Managing treatment plants for water reuse in agriculture

Traditional wastewater treatment plant technology has been developed to minimize organic pollution, and in some cases N and P pollution, from TWW with respect to normative constraints. In most cases, wastewater is treated in such a way that organic content is minimized (as indicated in the experiences reported in the first section, most treatments to produce TWW are conventional activated sludge processes). To ensure sustainable reuse, which encompasses a notion of the benefit of water in agriculture, wastewater should be processed in such a way that the organic and mineral contents contained in the water meet agronomic needs. Indeed, as stated above in the Tunisian case, the fertilizing potential of wastewater is significant. More generally, in the average Mediterranean case, for an irrigation of 700 mm/ha/year, the quantities of nitrogen and phosphorus contained in wastewater treated by activated sludge without denitrification are 150 and 50 kg respectively, which would represent a large proportion of the fertilization requirements of a crop (Condom et al. 2012). However, the application of nitrogen at levels higher than required for crop growth may present risks for crops and/or groundwater.

Crop needs are highly dynamic. Consequently, the treatment system must be designed and operated in such a way that treated water could contain low nitrogen/phosphorus during no-irrigation period (e.g., during low plant uptake stages) to limit environmental impacts. This is particularly true for N-sensitive areas:

- Recovering N and P from the total sewage water produced worldwide would lead to a saving of 33 and 22%, respectively, in N and P fertilizers (World Bank 2010).
- According to the World Bank, irrigation with TWW (activated sludge without denitrification) can meet 53, 50, and 31%, respectively, of nitrogen, phosphorus and potassium needs.
- Regarding long-term studies, the organic carbon contained in soils should play an important role, not only in the soil function but, also, in the global Carbon cycle (Lal 2004; Drechsel et al. 2010). Increases in the organic carbon content of soils would be an advantage from an environmental viewpoint, especially for areas where desertification is seen as a tangible risk.

Even if in a number of cases, users are willing to pay extra for higher water quality (cf. the Tunisian experience), this benefit has to be weighed against possible indirect costs. For instance, regarding the authors' experience in France, the Sainte-Maxime golf course has been irrigated since 2006 with TWW. Thanks to nutriments contained in the TWW, fertilizer consumption has decreased by 67%, although additional grass cutting is still required, which means that nutrient management could still be improved.

Assuming actual treatment technology can be used to modulate water quality, future challenges are likely to be ensuring that the organic and metallic micropollutants, as well as pathogen concentrations found in treated wastewater, comply with regulations, and the assessment of the capacity of the agricultural system to inactivate or degrade them. As underlined above, one of the main challenges to be addressed is to manage remediation processes that have been designed to remove pollution in such a way that they deliver water meeting specific quality requirements. In other words, the objective is no longer to deliver water with C, N, and P concentrations that are lower than normative constraints but, rather, with C/N/P optimal ratios (called "setpoints" in dynamic systems and control theory, and of particular interest within the present context) with respect to the specific needs of irrigated plants as well as soil storage capacity. Such setpoints should be designed from a dynamic perspective: in the short term, it is expected that the needs of plants may change over days or weeks; in the long term, on the other hand, they can change with respect to crop rotations, e.g., following recommendations and specifications detailed in rapidly developing agroecological approaches (Gliessman 2006). To achieve such objectives, automatic control theory may be of interest (Katebi et al. 1999). In particular, the use of a systemic (or input-output) approach may indeed be of interest when designing advanced feedback control laws[4] that aim at driving one or several outputs (C, N, and/or P concentrations) towards predefined setpoints possibly in real time, or in minimizing any other objective criterion. To design such feedback mechanisms, the use of models that capture the main dynamic properties of the system could be used. However, we do not know if available models that have been developed, notably by the International Water Association (IWA 2000), to simulate actual WWTP operations are suitable for this purpose. In other words, the flexibility of actual processes must be evaluated with respect to the new objectives we describe here. We believe this work must be done so that models and optimal control-based solutions—that have been proven to be relevant for decision-making in classic integrated water treatment, cf. for instance (Gajardo et al. 2011; Rapaport et al. 2014), seawater desalination (Yokokawa et al. 2013) or in an industrial framework (Dvarioniene and Stasiskiene 2007)—can be used within the new integrated approach we put forward in the present paper.

Irrigation technologies using recycled water

In some cases, regulations have been adapted to allow for a more integrated approach. This is true in the French case where constraints inherent to irrigation technology have been taken into account. For farmers, using TWW presents an additional constraint: the integrated system must be designed to take into account the risk of biofilm clogging or pathogen regrowth in the irrigation system and unintended dispersion (Ayars et al. 2007). Three distinct irrigation technologies are available for water distribution in an agricultural plot. These systems have different potential life durations, and each has associated risks of potential dissemination of unintended materials (pathogens and pollutants). These issues can be effectively managed using suitable practices designed to decrease the potential level of hazards.

Gravity or surface irrigation is the most widely used technique in Mediterranean agriculture and worldwide. It takes advantage of the potential energy of water to flood the plots as homogeneously as possible through soil leveling, regulation of plot inlet flow, and irrigation duration. With this technology, pathogens, or hazards from pollutant aerial dissemination, are restricted but the contamination of the soil, plants, and water tables may be significant. Widely used by traditional farmers, exposure by contact, and product ingestion, may have serious health consequences.

Sprinkler irrigation, which tends to reproduce homogeneous rainfall over the entire plot, restricts the potential contact of workers with contaminated waters, but the hazards involved are linked to unintentional dissemination of effluent in the form of fine droplets that may contain pathogens or other harmful contaminants when sprinklers operate under different wind regimes (Molle et al. 2016). On the other hand, both of these irrigation technologies have the potential to play a key role in pathogen control depending on the survival capacity of microorganisms during the transport and distribution process in air or soil. For instance, a decrease of two orders of magnitude of respiratory pathogens has been observed during the sprinkling dissemination process in wind tunnels. Except for *Legionella pneumophila*, such contamination routes remain poorly understood and merit to be addressed in research work.

Drip irrigation is widely promoted as a means to improve water productivity (Luquet et al. 2005), which is recognized when the system is brand new, but seldom over the long term. Drip irrigation has the potential for much greater efficiency than other irrigation techniques by applying water directly to the immediate vicinity of the plant, thereby increasing water productivity (Lamm and Camp 2007). Drip irrigation systems can also improve nutrient use efficiency (fertigation), decrease energy requirements, and improve cultivation practices (Ayars et al. 2007). When reusing treated wastewater, this technology is considered the best option in terms of protection against contact and the dispersion of pathogens. Nevertheless, its long-term performance continues to be questioned. The presence of nutrients and salts in WW increases the possibility of chemical precipitation as well as biofilm development due to the particles transported (Carpa and Scicolone 1998; Gamri et al. 2014; Rizk et al. 2017). In addition, clogging by sedimentation can soon lead to a sharp decrease in distribution performance (Bounoua 2010). A better understanding of clogging phenomena, and their interaction, demands new research on the characterization of flow topology inside narrow labyrinth channels, on biofilm characteristics and their response mechanisms while taking into account both nutrient transport and hydraulic shear force, as well as analysis of chemical precipitation.

Cropping systems and soil and groundwater impacts

Soil properties, and soil organization in the landscape, both vertically and laterally, strongly influence water transfer and

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[4] "Feedback control" refers to the appropriate way of acting on a physical system—through actuators—to force certain output variables—usually observed via measurements—to follow predefined possibly, time-varying patterns called "setpoints."

its availability to plants, while groundwater quality depends heavily on biogeochemical processes in the unsaturated zone. These points are crucial for the protection of soil fertility against risks linked to salinization, alkalinization, and soil structure degradation. The impact of wastewater on agricultural soils is mainly due to its high nutrient content (nitrogen and phosphorus), high total dissolved solids, and other constituents such as heavy metals which accumulate in the soil over time. Wastewater can also contain salts that may accumulate in the root zone with possible harmful impact on soil health and crop yields. The problem of soil salinity and sodicity can be resolved by the application of natural or artificial soil conditioners. However, such soil reclamation measures are costly, thus adding economic constraints that can result in crop productivity losses. Moreover, it may not be possible to restore the soil to its original level of productivity by using such soil conditioners. Therefore, wastewater irrigation may have a long-term economic impact on the soil which in turn may affect market prices and the land values of saline and waterlogged soils.

The leaching of salts below the root zone may cause the pollution of both soil and groundwater (Bond 1999). Applying wastewater has the potential to damage the quality of groundwater resources in the long run through the delivery of excess nutrients and salts caused by wastewater leaching below the plant root zone. However, the actual effects depend on various factors including depth of the water table, the quality of groundwater, soil drainage, and wastewater in irrigation. The proximity of wastewater irrigation to sources of potable water supplies, such as wells or tube wells, will influence how we evaluate the severity of groundwater exposure. Thus, the potential for groundwater contamination needs to be evaluated before embarking on a major wastewater irrigation program. In addition to the accretion of salts and nitrates, wastewater irrigation can, under certain conditions, transfer pathogenic bacteria and viruses to groundwater (NRC report 1996).

Wastewater (treated and untreated) is used in agriculture because it is a source of macronutrients (NPK) and micronutrients (Ca, Mg, Mn, Se …) and provides all the moisture necessary for crop growth. Due to this nutrient content, most crops give higher than expected yields with wastewater irrigation when compared to standard fertilization of irrigated crops, which does not include any micronutrients, thereby reducing the need for chemical fertilizers, which results in net cost savings for farmers. Furthermore, the high concentration in untreated wastewater of plant nutrients becomes an incentive for farmers to use it as it reduces fertilizer costs, even when the higher nutrient concentrations may not necessarily improve yields. Most crops, including those grown in periurban agriculture, need specific amounts of NPK for maximum yield. Once the recommended levels of NPK are exceeded, crop growth and yield may be negatively affected. The different experiences reported in the first section of this paper attest to the fact that this negative effect has been observed in a number of cases, for instance in Tunisia.

Such aspects are generally not considered by reclaimed water use project planners, yet the close connection between treatment management and the potential crop reuse of nutrient is of high interest (if well controlled as we suggest above), at least in terms of energy balance (e.g., nitrogen removal from a wastewater requires additional energy to be injected—through aeration in an activated sludge treatment plant; it uses up to 40% of the energy needs, while 1 t of nitrogen fertilizer required 1 t of petrol equivalent energy).

Sanitary pollution via wastewater reused for irrigation

As shown in the different national cases reported, the wastewater reuse experience in reducing health risk is very low whatever the country considered (too many parameters to be monitored, very few long-term experiments, lack of political will …). However, effluents emanating from urban WWTP are suspected to be among the main anthropogenic sources of pathogens, antibiotics, antibiotic-resistance genes (ARG), and antibiotic-resistant bacteria (ARB) released into the environment (Verlicchi et al. 2012; Rizzo et al. 2013; Yang et al. 2014). Indeed, biological treatment processes create an environment that is potentially conducive to both resistance development and its spread because WWTPs are in fact reservoirs for microbial diversity in ongoing growth which is continuously mixed with antibiotics at sub-inhibitory levels. But WWTP also involve different biological and physical-chemical processes which may affect the fate of antibiotics, ARB, ARG, and pathogens. Michael et al. (2013) showed that antibiotic removal efficiency varies and depends on the combination of an antibiotic, its physical-chemical properties, and operating conditions. They argued that membrane processes, activated carbon adsorption, or advanced oxidation processes (AOP) may lead to higher rates of removal, and may be necessary before final disposal of effluents or recycling for irrigation; however, less is known on such processes when they are run under sub-optimal conditions. The effectiveness of integrated processes, including membrane bioreactors and AOP, was investigated for wastewater from pharmaceutical production, while also taking into account by-products from degradation (Pollice et al. 2012; Laera et al. 2012). This aspect of degradation by-products is especially relevant when considering that many complex molecules are only partially degraded through chemical or biological processes: accurate monitoring of degradation by-products should be carried out in order to evaluate their persistency and possible toxicity (Mascolo et al. 2010). Moreover, very little is known about the implications for soil/crop irrigation of the distribution system/point-of-use (Fahrenfeld et al. 2013). Various biological contaminants (human and animal pathogens, phytopathogens, ARG, ARB) can be transported by wastewater and be enriched in soil. Several technologies exist for an efficient removal of contaminants from TWW, but several questions remain to be addressed such as the dynamics of contaminants during the transport and distribution of water or the effects on soil microbiota which was also neglected in most studies on irrigation with wastewater (Becerra Castro et al. 2015). Heavy metals have been shown to accumulate in the soil at toxic levels as a result of the long-term application of untreated wastewater. Soils irrigated by wastewater accumulate heavy metals such as copper, zinc, cadmium, and nickel in top soil. When the capacity of the soil to retain heavy metals declines due to repeated applications of wastewater, heavy metals may leach into the groundwater, thus becoming available for plant uptake (Devkota and Schmidt 2000; Frost and Ketchum 2000).

Social aspects of irrigation with wastewater

In arid and semi-arid Mediterranean areas, the reuse of TWW faces many socio-economic challenges such as evolving legal frameworks, local cultural conditions (especially in Islamic countries where there are religious restrictions about the use of "impure" water although Fatwas have been issued to allow use of reclaimed water in several Muslim countries), social and economic considerations, and farmer involvement in issues related to agricultural water supply, etc. Acceptability of this type of new water resource is a crucial issue and requires the full and real participation in the decision-making process of the different stakeholders.

Under certain specific conditions (IWMI 2007; MED WWR WWG 2007; World Bank 2010; El Ayni et al. 2011; Condom et al. 2012; Mizyed 2013), projects involving TWW reuse can contribute to an integrated management approach to water resources that reconcile different goals such as the fight against poverty, economic development, environmental and human health protection, etc. From a socio-economic point of view, water reuse represents a hybrid research object located midway between supply-side and demand-side approaches, and involving both technological and socio-economic challenges, while at the same time introducing into the public debate the idea of water recycling at the scale of a given territory. This is why, as underlined above, water demand management, which involves making better use of available resources—as opposed to simply always augmenting supply—is gaining traction as a way to mitigate water-scarcity problems (Winpenny 1997).

The issue of safe wastewater recycling in agriculture thus cannot be reduced to its mere technological, quantitative, and qualitative aspects (fulfillment of more or less strict environmental standards), but must also include a number of other socio-economic aspects and the challenges involved in integrating different scales of analysis. Before adopting one given technical solution, end users need to know and understand the economic costs, returns, and benefits associated with the different qualities of TWW. In many cases, the experience tends to prove that any technology transfer mainly benefits the investors (national and international) who have considerable financial means and lobbying capacity; it seldom benefits small farmers who already have poor access to water and sanitation. In a socio-economic context that is increasingly affected by globalization, and confronted with extreme poverty and highly differentiated agricultural production systems, the question remains how to prevent irrigation water reuse projects from resulting in increasing inequality?

Adapting to climate change in general, and for the water sector in particular, requires a wholesale move away from a short-term reactive or curative approach to the preventive and proactive management of risks and resources over the long term. Water reuse projects form part of these potential resources for agriculture and fully fit the principles for action underpinning this type of management: promoting innovation, long-term planning, and opting for "no regrets" or "few regrets" measures that create win-win situations, and that encourage dialog between all stakeholders in the water sector (Plan Bleu 2012). Citizen grievances that drove the "Arab Spring" stemmed in part from the lack of accountability of executive branches of government and the failure to deliver basic services linked with good governance. In this context, recent social and political changes in Tunisia or Morocco underscore the need for "increasing transparency, the decentralization and the empowerment of local civil society support and the re-appropriation of water, livelihoods and power" (Houdret 2012).

Conclusion

In the changing climate context around the Mediterranean Rim, it is expected that rapidly expanding water-recycling practices will quickly provide sustainable, low-energy, and cost-effective options to improve water availability based on criteria of quality and recycling capacity. To do so, processing systems must be rethought by adopting a bottom-up approach from use to source, by evaluating different scenarios in terms of environmental assessment techniques and risk analysis using standardized methods (as cost-benefit analysis, life-cycle assessment[5]), and by ultimately making a real paradigm shift from a wastewater treatment plant to a water resource recovery facility, thus creating a real environmentally friendly "biorefinery" within a more circular economy framework. Apart from agriculture, several studies have been carried out to assess other reuse options such as groundwater recharge as well as municipal, industrial, and environmental applications. The studies have shown that strategy should be focused on the substitution of conventional water by reclaimed water.

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[5] Abbreviated as LCA (see Online Resource 3)

Forthcoming projects aimed at meeting a real demand for water—in quantity and quality—should encourage a greater utilization of reclaimed water, primarily for agricultural purposes, and thereafter, in other sectors.

As the water reuse cycle is essentially an interdisciplinary issue, an integrated approach encompassing social and economic along with environmental concerns should be used to address it. In particular, at the local level, a sensible cost-benefit approach will have to take into account, both the financial and non-financial benefits. To this end, innovative research is needed on the potential impact of reuse techniques and practices, possibly including innovative decentralized treatment techniques that facilitate the conservation of those compounds that are beneficial for plants.

Regulations will then need to be redrafted in a more consistent and standardized way, and thereafter more effectively enforced worldwide to make a wiser use of the precautionary principle (Molle et al. 2012). Treatment plant design should fully integrate reuse concerns to ensure the value of reclaimed water. The wastewater treatment industry also faces a new challenge: delivering treated wastewater fit for agriculture purposes rather than treating water to minimize its impact when disposed of in the environment. There are obviously two possible routes. The first is to adapt the quality of the water based on environmental and health constraints. Treatments should also be economically affordable, but further research is needed to evaluate the potential health and environmental risks and societal acceptance of this solution. The second more technological route aims to use high-performance treatment systems to remove all possibly problematic compounds, then to selectively recover those that can be of positive use (as N, P, K, or micronutrients), and finally to irrigate crops/plants in a totally secure and adapted way. This latter option remains a possible alternative, but its success will depend on our ability to recover compounds of interest in a cost-effective way, and this remains the major obstacle. Such potential developments should address health and pollution hazards and reduce the treatment footprint and, more generally, the human waste footprint (water as well as energy). This would maximize the opportunity offered by agriculture for recycling (with precautions of use) preferably for non-food crop irrigation, but also some food production (raw or cooked food crops) after specific treatment. In addition, this implies that the social and cultural aspects of water reuse are fully understood and that the population supports the idea, and moreover, is willing to pay for, or welcome a water reuse project. Linking reuse policies to the possible advanced resilience of human communities, the water cycle in their various environments should be explained clearly to local populations who may always remain reluctant. Experience in Mediterranean countries that have long practiced reuse (e.g., Jordan, Tunisia, France, and Italy) can greatly facilitate this task as well as the efforts of international organizations (WHO, FAO, CEN, ISO, …). By upgrading water quality and providing more widespread information, reclaimed water reuse should gain wider acceptance in the near future (Bahri 2009).

Funding information The authors thank for their financial support the SICMED Mediterranean research network (http://www.sicmed.net/), the TREASURE research network (https://project.inria.fr/treasure/), the UTIQUE project 2013 No. 28687SF “Ecologie microbienne et modélisation pour le traitement de l’eau,” the TASSILI project 2015 No. 33254QH “Procédés membranaires pour le traitement anaérobie des eaux usées—Modélisation, commande et optimisation,” the Water4Crops FP7 project, “Integrating bio-TWW with enhanced water use efficiency to support the Green Economy in EU and India,” No. 311933, the Mad4Water EU Horizon 2020 project, “Development And application of integrated technological and management solutions for wastewater treatment and efficient reuse in agriculture tailored to the needs of Mediterranean African Countries,” and the NOWWMA project, “New Process for Optimizing Wastewater Reuse from Mauguio to the Mediterranean Area” in support of the French Reuse Directive.

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