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Criteria and operational guidelines to increase wastewater recovery on islands and in rural areas

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ABSTRACT

Although the main function of wastewater stabilization reservoirs (WSRs) in agriculture is to allow the storage and temporal shifting of large volumes of water for irrigation, further benefits can be achieved from their application in a wastewater reuse system. Under proper management conditions, significant improvements of the water quality for irrigation can take place as a result of concurrent physical, chemical and biological processes. Here, a multi-seasonal, WSR-based procedure has been proposed and simulated in terms of operational parameters in order to reduce the effects, particularly critical during the irrigation period, of the introduction of fresh effluents on the quality of stored water. Furthermore, an appropriate use of high-rate algal ponds has been suggested as an alternative to the nutrient removal phase in the wastewater treatment plant.

Keywords: Wastewater reuse; Operational index; HRAPs; Microbiological quality; Stabilization reservoir; Costs

1. Introduction

Many countries throughout the world struggle to cope with water resources that are increasingly limited in both quantity and quality. As a consequence, the water utilities that manage potable water and wastewater treatments have begun to incorporate planned water reuse strategies as a part of their sustainable water resource management policies [1,2].

Whenever wastewater effluents are used, health protection measures need to be enforced. In the past, it was widely accepted that resorting to wastewater treatments with certain restrictions, according to the type of crops, would provide a sufficient level of health protection when wastewater was used in agriculture (low risk). The World Health Organization has indicated that effective health protection can also be achieved through the integration of various control mechanisms, such as wastewater treatments, crop restrictions, the control of wastewater application and human exposure controls [2].

Some countries (e.g., Italy, Spain, and California) have preferred to follow a more restrictive approach, totally focused on the wastewater treatment plant (WWTP) performance, in which high quality standards are required for the effluent reuse, standards which, at least as far as some parameters are concerned, are surprisingly similar to those applied for drinking water [3]. This approach has often led

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to insuperable difficulties in promoting wastewater reuse, as compliance with these very strict standards requires advanced treatments and results in unaffordable costs for farmers, especially if compared with the costs of water from superficial water bodies or groundwater.

Moreover, the overabundance of required parameters (e.g., 54 parameters in the case of Italy), as well as their related monitoring protocols [4], has had important consequences on the economics of the reclamation of wastewater and has further hampered the chance of reusing it, since the final costs (construction, operation and maintenance [O&M]) of reclamation, in addition to the costs for water distribution and monitoring of the reuse system, are barely sustainable for small-to-medium wastewater reuse systems [5].

A new holistic multi-disciplinary and sustainable approach to wastewater reuse for irrigation should be considered, especially for small-to-medium urban communities of islands and rural areas, in which the overall policy-making, engineering design, monitoring, surveillance, management, administration, legal and environmental aspects should be taken into consideration. This approach should involve combined health, environmental and economic benefits for the urban communities (which free themselves of wastewater) and economic and livelihood benefits for the rural community (which uses it) [6].

The choice of appropriate and sustainable wastewater reuse schemes should be based on a careful analysis of all the aforementioned elements, considering their potential role of guaranteeing the global financial soundness of the project, as well as the necessary environmental and sanitary requirements [7]. The aim of this paper is to emphasize the role of wastewater reservoirs as a further sanitary barrier within the reuse system, by proposing a multi-seasonal, multiple wastewater stabilization reservoir (WSR)-based procedure able to optimize their management, here simulated in terms of operational parameters.

2. The 'other' role of storage in wastewater reuse systems

Among the various functional elements of a wastewater reuse system, storage plays an important role in preventing the discharge of treated wastewater into water bodies and, at the same time, it allows the continuously produced volumes to be utilized during the narrow period of the irrigation season.

Several researches [8–12] have established that, under proper operation and conditions, storage inside a wastewater reservoir can lead to a significant improvement in the quality of water for irrigation, as a consequence of a complex system of physical–chemical and biological processes, which are typical of hypertrophic water bodies with slow water turnovers.

In particular, during the long detention periods of the non-irrigation season, the bio-antagonism processes lead to a progressive reduction in the number of indicator microorganisms and pathogens [4]. Removal effectiveness is generally improved by means of a stable stratification, which determines a barrier between the upper aerobic layer and the lower anaerobic one that is in contact with the sediments [13,14]. However, the presence of a stable stratification can cause hydraulic short circuits and a consequent reduction in the 'active' volume and mean retention time (MRT) [15,16]. Solar radiation and the production of oxygen, associated with high pH values, are considered the main parameters in the die-off of pathogens in stabilization ponds [17–19]. Even in WSRs, the polishing performance depends on establishing a positive balance between algal photosynthesis and the oxygen demand exerted by bacteria during organic matter decomposition [20,21]. Also, the simple sedimentation process also plays a key role in the reduction of the suspended solids and attached microorganisms (included helminth eggs), which significantly improves the chemical–physical and microbiological quality of the stored wastewater.

The role and importance of the operational parameters, such as the MRT, in governing wastewater quality in a reservoir is well acknowledged [8–10,22]. Several authors [21,23–25], pointing out the non-steady-state features of stabilization reservoirs, have indicated that PFE_ns (i.e., the percentage of effluent with a detention time of *n* days or less) were the main parameters linked to the removal of the total coliforms and of the organic content.

The percentage of (fresh) effluents with a one-day residence time, when outflow (OUT) occurs, is expressed by:

$$PFE_{id} = \frac{IN_d - \left(IN_d \times \frac{OUT_d}{VOL_d} \right)}{VOL_d} \times 100 \tag{1}$$

A simple algorithm can be implemented to evaluate PFE*n* for any value of *n* (days).

When a reservoir operates as a cumulative batch reactor, during the non-irrigation season, both MRT and PFE*n* continuously vary over the year. MRT increases during the non-irrigation period, reaching a maximum towards the middle of the irrigation season. PFE*n*, with a high value of *n* (≥30 d), decreases during the non-irrigation season, because of the growing volume inside the reservoir, but increases to a great extent during the irrigation season, due to the continuous reduction in the stored volume (and limited dilution of the incoming treated wastewater). When a reservoir operates in a batch mode, the volume is filled altogether, and the significance of the operational parameter PFE*n* decreases while that of MRT increases. Cirelli et al. [4] introduced a new operational parameter, MRT %FE, and combined it with first-order kinetics, to model the concentration of *Escherichia coli* in WSRs; a fairly good agreement was found between the measured and predicted bacteriological concentrations. In order to take into account the hydraulic depth, as well as the surface area of the reservoir, Mancini et al. [11] proposed the following combined operational parameter:

$$PFE_5H = (1 - PFE_5)\left(\frac{A}{V} * h_{max} \right)^{2,5} \tag{2}$$

High correlation values were found between the microbiological characteristics of the water stored inside a wastewater reservoir and the proposed operational index, which, together with the 'fresh effluent' input effects, correlates the hydrodynamic boundary conditions, contributing to the removal phenomena, through an inverse relation with the non-dimensional hydraulic depth.

3. Issues that need to be solved in the management of WSRs

Some important issues have to be faced in order to optimize the reuse system management through the 'finishing' role of the different storage capacities on the wastewater quality for irrigation.

3.1. Excessive algal production and clogging issues

The dynamics of the planktonic community of wastewater reservoirs is of great importance, in consideration of the destiny of the stored water (i.e., irrigation). The introduction of fresh wastewater into a reservoir, and the related nutrient load, can lead to drastic changes in the planktonic community, with the substitution of many small-sized organisms (chlorophyta–diatoms) with a less number of larger-sized organisms (Cyanophyta–Euglenophyta), and a consequent remarkable increase in volatile suspended solids, chlorophyll and pH [23]. The consequent development of large populations of cladocerans (0.2–6 mm) and copepods (1–2 mm) in reservoirs can dramatically increase the possibility of sprinkler clogging when drip irrigation is used. Milstein and Feldlite [14] studied the relationship between filter clogging and particle-size distribution in secondarily treated wastewater reservoirs. During the irrigation season, the authors identified an important correlation between thermal stratification and the development of a planktonic community with a complex web of feeding interactions in which the most likely organisms capable of clogging filters were copepods. In spring and autumn, the main organisms responsible for filter clogging were cladocerans, involved in a shorter food chain. Organic and nutrient loading, which are prevalently related to the introduction of fresh wastewater into the reservoirs during the irrigation season, were found to have a negative effect on nitrification and to promote the development of blue-green algae and the reproduction of copepods [26]. A reduction in the nutrient load introduced with the fresh effluents is thus highly recommendable to avoid clogging issues. Unfortunately many small- to medium-sized WWTPs, especially in the southern areas of Europe, still suffer from the design-lack of a nutrient-removal phase, and its introduction into the original WWTP layout could be made difficult because of space and hydraulic profile constraints.

3.2. Compliance with the stringent standards required for unlimited irrigation

Apart from the increase in algal production, the addition of fresh wastewater during the filling of WSRs can also cause a severe deterioration of the quality of the stored water, as far as the microbiological parameters are concerned [24,27]. Other researchers [4,12,25] have confirmed that, despite the WSR removal efficiency of several physical–chemical and microbiological pollutants (e.g., salmonella and helminth eggs), in a continuous operational regime effluent rarely satisfies the most restrictive standards (e.g., the Italian ones) pertaining to *E. coli*. By reviewing and evaluating the statistical data of 60 WSRs in Israel, a country in which the storage of treated wastewater has been widespread utilized since the early 1970s, Kfir et al. [28] found that most WSRs met the biochemical oxygen demand (BOD) and total suspended solid (TSS) values (65% and 80%, respectively), required for unlimited irrigation by the standards in force at the time of the study, but most of them failed to meet several of the new quality parameter requirements set in the new, more stringent 'Inbar' regulations, (i.e., *E. coli*, TSS, BOD and, to a lesser extent, faecal coliforms, chloride and sodium). However, it should be observed that most of the studied WSRs operate under a continuous flow regime, with 49 out of the 60 based on a seasonal storage-single WSR concept, while only 11 were based on a multi-seasonal, multiple WSR concept (i.e., relying on two WSRs working in tandem).

3.3. Costs of the wastewater and benefits of including WSRs in wastewater reuse systems

The European Union, through the Water Framework Directive (Directive 2000/60/EC) [29], stipulates that the price of water should include all the costs of the service (including environmental costs). Sipala et al. [30] obtained the unit cost of treated water from several different treatment processes and regeneration options; Lazarova et al. [31] indicated a 0.4–1.2 €/m^3 range as the cost of treatment for the reuse of wastewater in irrigation processes without restriction (coagulation/filtration/disinfection). A similar value (0.36 \$/m^3) was reported by Fine et al. [32], while a lower cost (0.2 €/m^3) was indicated by Gomez et al. [33] for larger plants. These costs are still far from the groundwater costs (0.1 €/m^3 or even less). No detailed information has been found, in the scientific literature, on the cost of wastewater storage in reservoirs, although this phase, conceived as a part of the treatment, appears to be a cost-effective option for both construction and O&M, as both the energy and maintenance requirements are low. On the other hand, these systems require the availability of large areas so they can represent a sustainable alternative to more intensive treatments, above all in rural areas, where sufficient low cost land is generally available. Indicative costs of construction (not including the cost of the land) for a sealed reservoir of 150,000 m^3 can vary between 4 and 6 €/m^3. This reference capacity corresponds to the storage of the wastewater produced by about 10,000 inhabitants for 3 months.

The main advantage of storage in stabilization reservoirs remains the possibility of recovering the high volumes of wastewater that are produced during the non-irrigation seasons and preventing them from being discharged into water bodies. Compliance with bathing standards could be more easily achieved and maintained, especially as far as the islands and coastal areas in Italy (e.g., Sicily) are concerned, if large volumes of treated water were transferred from coastal areas (the most heavily populated areas) to inland ones. This would allow the water resources to be available where and when needed, and to shift the storage facilities to areas with lower land prices. However, the construction and O&M costs (e.g., pumping) of transferring the resources might vary to a great extent and could even be unsustainable as a result of the morphological features of the coast–inland areas and the distance from the irrigated sites [4]. In order to distribute the economic burden of reclamation and reuse, it could be established that the construction, O&M costs of reclamation should be added to WWTP treatment costs and charged to the users of the water utilities, while the monitoring and distribution costs could be charged to the final users (farmers, golf courses, etc.).

4. Suggested layout and management criteria

Treated wastewater storage can play an important role in the holistic approach that is needed to identify appropriate and sustainable wastewater reuse schemes. The monitoring of the phenomena involved in the storage of wastewater in a small farm reservoir (FR), subjected to variable operating conditions [11], has confirmed what has been observed in many larger WSRs [9], in terms of changes in water quality and improvements. High removal efficiencies were observed (up to five log units with a 31-d MRT) during batch operating conditions, thus underlining the further sanitary-barrier role that also FRs can play. In areas where the mean size of the farms is small (e.g., some islands and semiarid rural areas) and water-rotation distribution practice is adopted, almost any farm has necessarily its small farm reservoir. The inclusion of these small reservoirs, in symbiosis with large WSRs in a reuse system layout, should be regarded as a further sanitary barrier, thus increasing safety for both farmers and irrigated product consumers. Anyway, in driving the design and management criteria of both small and large WSRs, beside economical and boundary conditions (climatic conditions, features of the existing water distribution system), main efforts should be addressed to minimize the fresh effluent input to volume ratio [24].

4.1. The proposed wastewater reuse system layout

A set of design and management criteria has specifically been conceived to limit the deterioration of water stored in reservoirs, caused by the introduction of fresh effluents. The proposed solution was targeted to the case of Mediterranean regions and islands (e.g., Sicily), where small reservoirs, already present on several farms, could be possible candidates for inclusion in a 'traditional' reuse system layout. The proposed reuse scheme involves the insertion of three 'new' reservoirs (Fig. 1). It has also been proposed to include a high-rate algal pond (HRAP) following the secondary treatment to help reducing nutrients and to improve microbiological quality [34–36]. HRAP is followed by a filtration phase (to remove residual organic matter and allow the harvesting of the algal biomass) and a disinfection phase (optional). The following storage phases (through the tandem use of seasonal stabilization reservoirs) can be regarded as a further microbiological barrier; therefore, increasing the overall sanitary safety of the reuse system while maximizing the wastewater recovery [7].

4.2. Management and operational criteria

The suggested operational management for the 'modified' reuse system includes the following steps (Fig. 2):

Step I – December, January and February.
From December 1, WSR1 is empty, WSR2 is full and WSR3 is filling up and will be full by the end of February.

Step II – March, April and May
Starting from March 1, WSR1 is filled with wastewater coming from the treatment system. WSR3 is full of a volume of wastewater that is the total of 3 months (December–February), stops receiving fresh wastewater. The 'long-term stored' water in WSR2 is transferred (when necessary) to the small FRs to be ready for the irrigation procedures. However, the farmers are asked to wait 3 d before

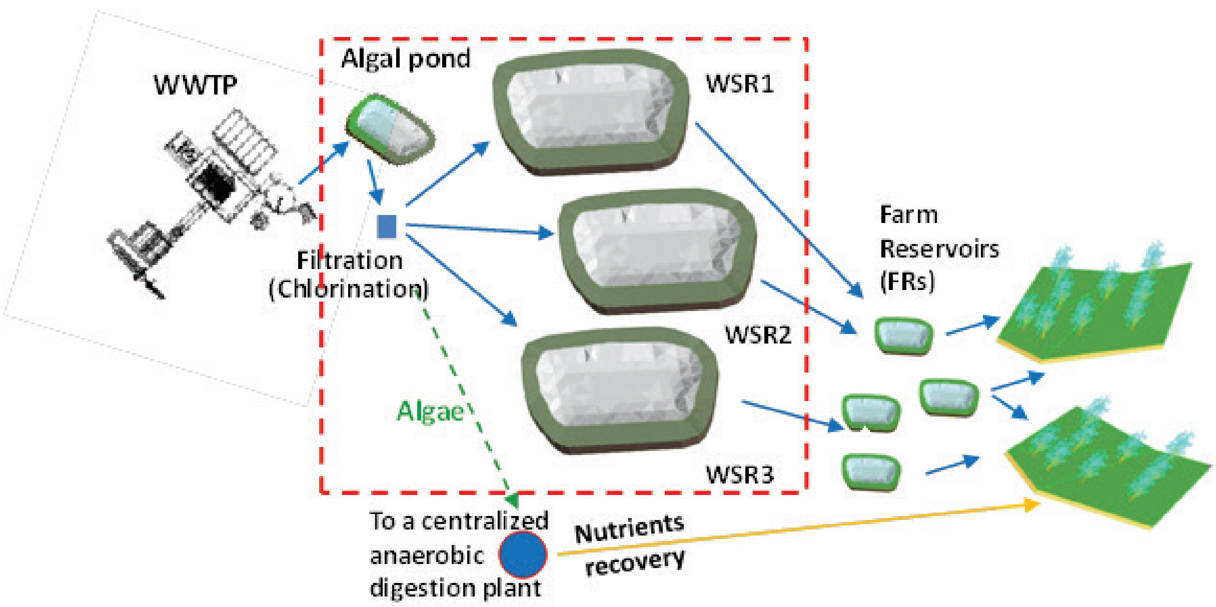

Fig. 1. Sketch of the wastewater reuse system with the proposed modifications (dashed rectangle).

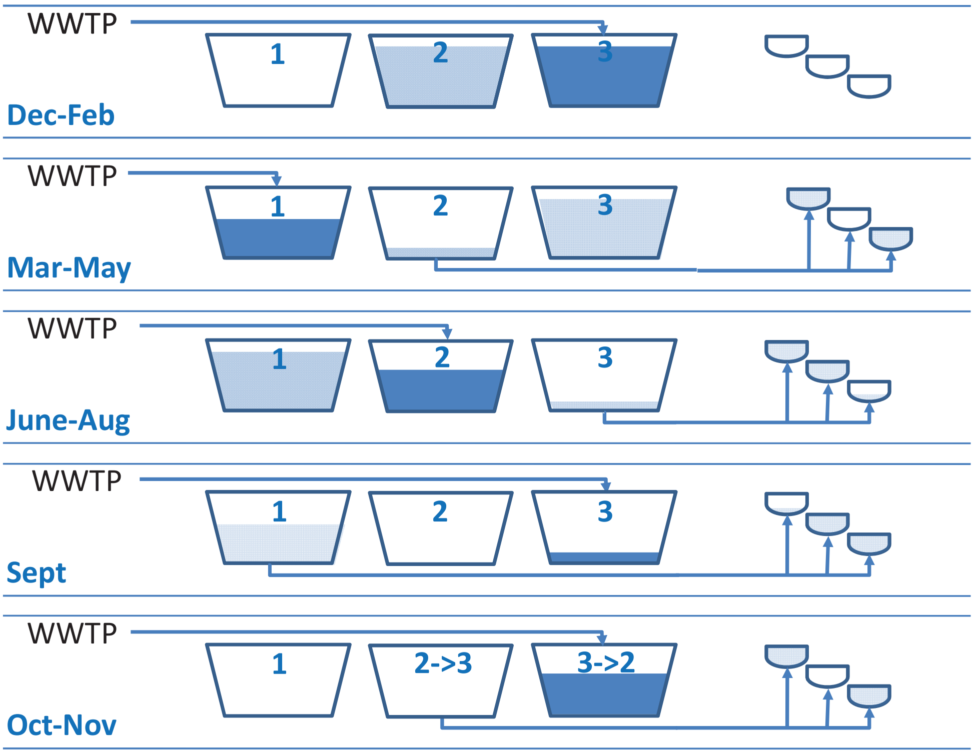

Fig. 2. Proposed operational management of the three WSRs.

using the water for irrigation in order to reduce any fast filling effects.

Step III – June, July and August
The farmers continue to irrigate with water from the FRs. WSR1 stops receiving wastewater. 'Fresh' wastewater from the plant is stored in WSR2 over the 3 months. All the long-term stored water in WSR3 is transferred to the small FRs to be used for irrigation.

Step IV – September
All the 'long-term stored' water in WSR1 is transferred to the small FRs to continue irrigation. The 'fresh' wastewater from the plant is stored in WSR2. The wastewater in WSR2 is stored ('aged') for at least 30 d in order to reach a zero PFE_{30} value. However, an additional 15 d of storage can be performed during the first 2 weeks of October to improve the water quality, if needed, before the water is transferred to the FRs.

Step V – October, November, and December
The water from WSR2 is transferred to the FRs for the last irrigation, while WSR3 continues to be filled with fresh wastewater. WSR3 will in fact become the 'new' WSR2, while the 'old' WSR2 will become the new WSR3, thus re-starting the cycle.

The management procedure here suggested to avoid filter clogging could involve (1) pumping water from the upper hypolimnion layer near the oxic epilimnion in order to reduce the problem of smell and controlling the clogging impacts of anaerobic bacteria in the distribution network; (2) using a bottom-up action to reduce phytoplankton by controlling the entrance of nutrients and/or reducing the introduction of light into the reservoir. Reducing light penetration is an option for which several floating cover technologies, which were originally developed to control evaporation in ponds and reservoirs, are available [26]. Their application would depend on cost/benefit considerations, and it should be taken into account that this bio-manipulation would probably constitute an effective tool against spring filter clogging caused by cladocerans, but may be less efficient against clogging due to the occurrence of cyclopoid copepods throughout the whole irrigation season. The nutrient levels depend on the quality of the wastewater sources and could be cost-effectively controlled by appropriately exploiting the removal efficiency of the HRAP and separating the algae through filtration/centrifugation in the WWTP.

Wastewater provides a conducive growth medium for microalgae because CO_2 balances the Redfield ratio (molecular ratio of carbon, nitrogen and phosphorus) of the wastewater, and this leads to faster production rates, reduced nutrient levels in the treated wastewater, decreased harvesting costs and increased lipid production. Microalgae, by removing nitrogen and carbon from water, can significantly reduce the eutrophication in the WSR aquatic environment, and constitute a base for bio-fuel or bio-fertilizer production [37–39].

4.3. Simulation through the use of operational parameters

Fig. 3 shows the volume and inflow–outflow variations over the year inside the WSRs, according to the proposed management criteria. The mean daily wastewater production

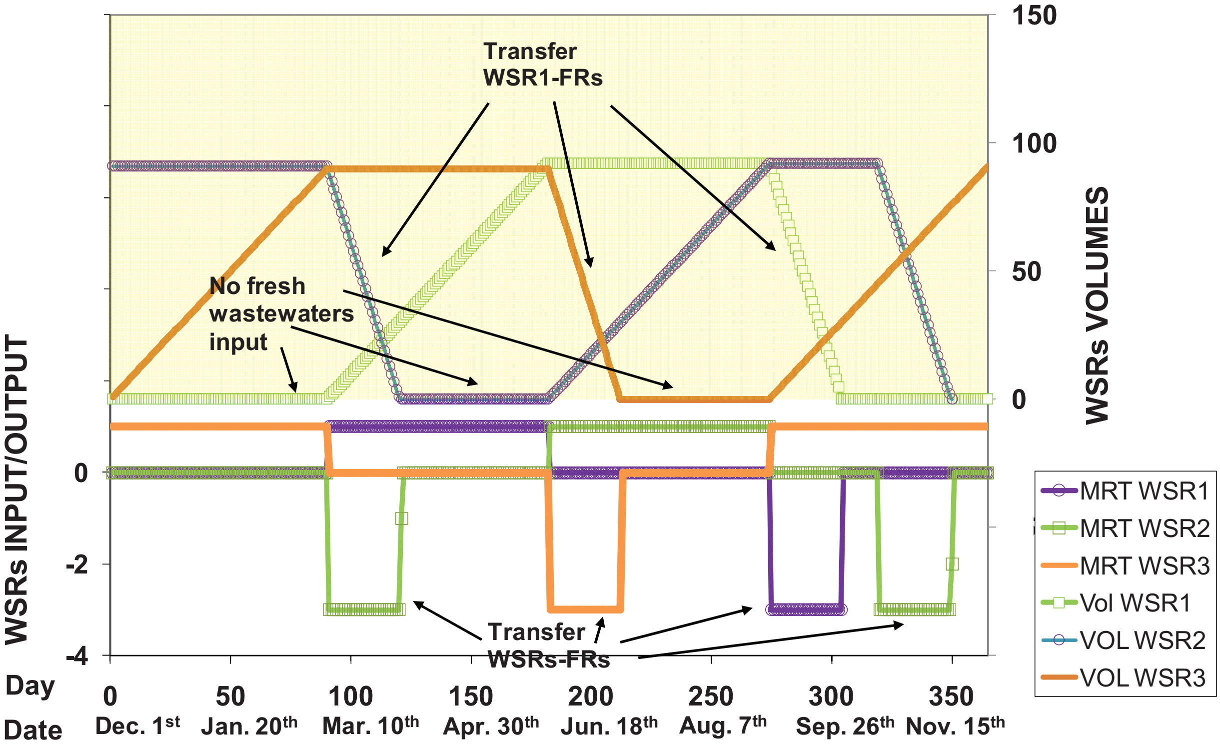

Fig. 3. Variations in the volume and inflow–outflow over the year in the WSRs (the unit volume is equal to 1 d of mean flow).

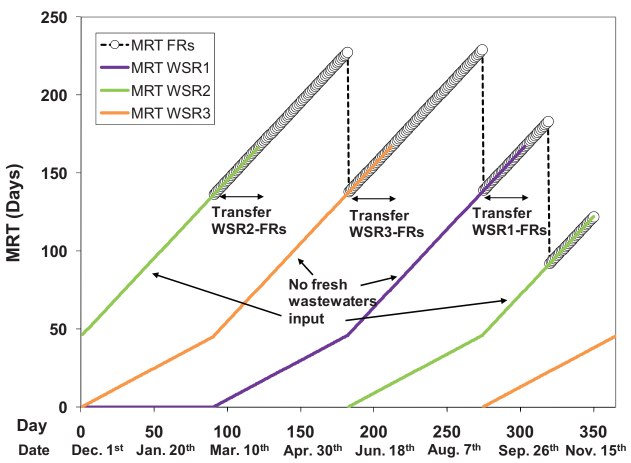

Fig. 4. Comparison of the WSR and FR mean retention times over the year.

is assumed to be unitary to easy generalize the obtained results to different sizes of the wastewater reuse system. Fig. 4 shows the simulation results, in terms of MRT variation, for wastewater stored in WSRs and FRs, respectively. Since MRT is a measure of the overall 'aging' of stored wastewater, it was decided to compute the wastewater detention time in the FRs in the analysis. Under this assumption, the MRT values of the wastewater inside the FRs can be calculated starting from the WSR ones (in the transfer phase).The MRT in the WSRs shows a constant increase rate during the non-zero input phases, followed by a sharper increase when the flow is stopped. The MRT of the FRs starts to be computed when the FRs are empty, and new wastewater arrives from the stabilization reservoirs during the four wastewater transfer phases from the WSRs to the FRs. Therefore, the minimum (cumulative) MRT values measured in the FRs are always at least equal to the maximum ones in the WSRs before the transfer is started. The minimum MRT values obtained in the FRs are 136, 138, 139 and 92 d, respectively, for March 1, June 1, September 1 and October 16 (end of the irrigation season).

Fig. 5 shows the results of the simulation in terms of PFEn values (5, 10, 20 and 30 d) for wastewater in the three WSRs.

Starting from December 1 (day 1), when the WSR3 begins to receive 'fresh' wastewater, all the PFEn parameters show a value of 100%, as the volume inside the reservoir is composed only of 'fresh wastewater'.

Later on, all the PFE$_n$s in WSR3, starting from PFE5, decrease with a regular trend till WSR3 is completely full (the wastewater is diverted to WSR1) and the PFE$_n$s all decrease in a faster way.

All the PFE$_n$s inside WSR1 reach a 0% value by the end of the detention period, before being transferred to the FRs, thus guaranteeing the quality of the water for irrigation, even though the farmers, contravening a suggested rule to delay irrigation for another few days, might immediately utilize the wastewater coming from the WSR.

As a consequence, the PFEn patterns in the FRs, which could be obtained according to the previously discussed concept of the cumulative 'aging' of wastewater, (i.e., starting from the values corresponding to the previous storage inside the large wastewater reservoir) are no longer significant for the considered PFE$_n$s (with n max equal to 30), and PFE$_n$s

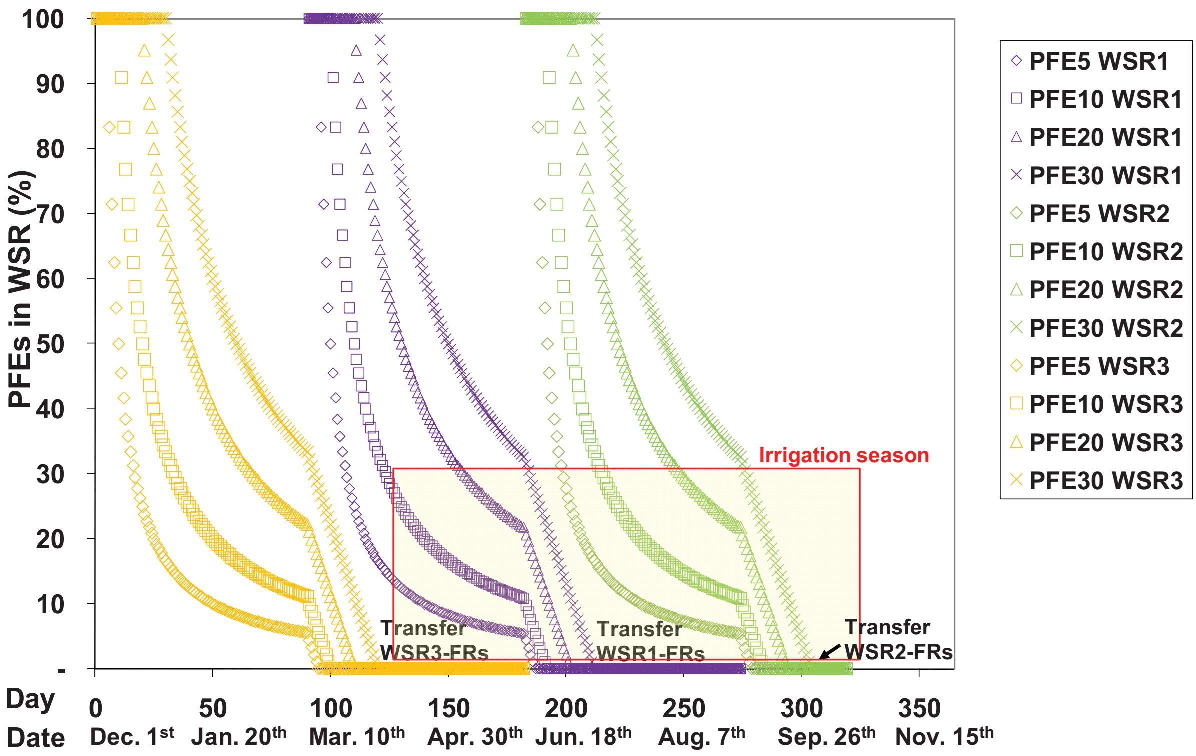

Fig. 5. Simulated variability, over the year, of the PFE*n* values in the three WSRs calculated for a different number of days (n = 5, 10, 20 and 30).

with higher n values should be considered. This result confirms the high quality achieved for the water in FRs.

In fact, WSR water is simply distributed to the FRs and no 'fresh' wastewater is added to the water stored in the FR and does not therefore interfere with the 'contamination' process, as expressed in terms of PFE*n* values.

Similar results, in terms of reduction in the 'fresh effluent' effects, are also obtained for the other two transfers from WSR3 and WSR2 to the FRs. On the basis of the previously described experimental results, as well as those reported in references [8,9,11,28,40,41], it can be stated that the farmers could rely on stored water of high quality for the irrigation procedures.

5. Conclusions

A wastewater reuse layout, including three large WSRs and FRs, has been proposed and simulated in the present work, considering PFE_n and MRT optimization. The storage phase has here been envisioned as a further finishing treatment of municipal effluents, after a tertiary treatment, in which a high-rate algal pond and a filtration phase are introduced to reduce the nutrients. The proposed three-reservoir-based procedure has the specific aim of reducing the effects of the introduction of fresh effluents on the stored water, which are particularly critical during the irrigation period. The adopted solution is particularly suitable for certain areas (such as Mediterranean regions and islands) in which many farms have their own reservoir, which should also be managed as a component of the reuse system.

High MRT and zero PFEn values (with n max equal to 30) were obtained in the simulation, as a result of the proposed layout and management criteria. These results, along with the high microbiological removal efficiency (for a wide range of MRT and PFEn values) that has been observed in several experiences throughout the world, suggest the possibility of having high quality water for irrigation purposes at affordable costs for the users.

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