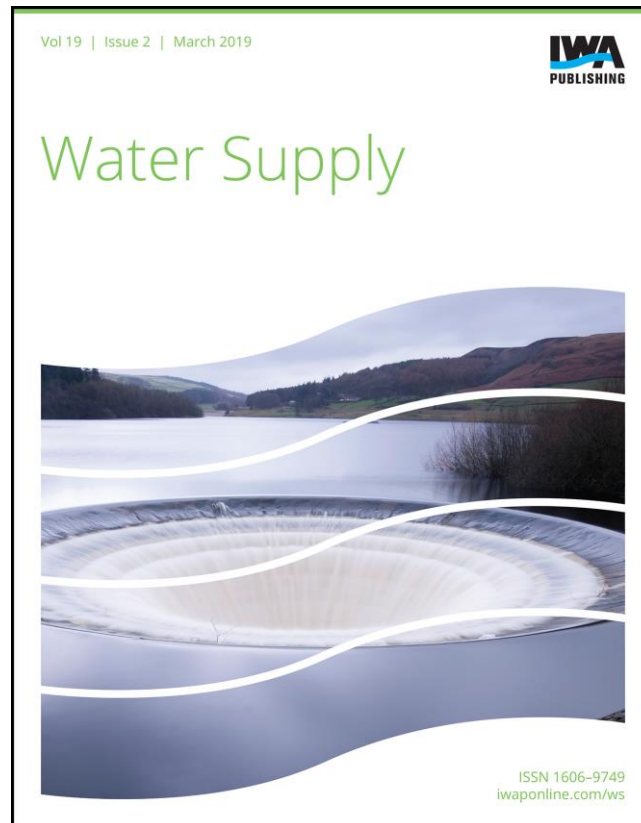


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Challenges for modern wine production in dry areas: dedicated indicators to preview wastewater flows

M. Oliveira, J. M. Costa, R. Fragoso and E. Duarte

ABSTRACT

Wine production is an important socio-economic activity in Mediterranean countries. This study is focused on wine production under warm and dry climate conditions in south Portugal, in two major wine-producing regions (Tejo and Alentejo), characterized by small to medium sized wineries. Vineyards have been expanding in this region of Portugal, where about 50–70% of the vineyards are irrigated, increasing regional water demand. The aim of this study is to propose an integrative approach for wine production, where a simple calculation model has been developed and validated to preview water consumption and wastewater production, as functions of winemaking periods and type of processed grapes. Results revealed a global ratio of 2.2 ± 0.45 and 2.1 ± 0.17 $L_{\text{water}}/L_{\text{wine}}$. Concerning dedicated indicators, 60–75% of the wastewater was produced during Period I and the red wine production represented a 50–64% increase in water consumption. This tool will enable winemakers to calculate Global and Dedicated Indicators, based on their own parameters, which provide information on flow volumes and peak flows. In this context, it will be possible to identify improvements for wastewater treatment and management towards water reuse as a promising solution for the wine sector in the framework of the circular economy.

Key words | Alentejo region, sustainable wine production, water management, water metrics, water scarcity

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ABBREVIATIONS

BAT best available technics

BOD biochemical oxygen demand

COD chemical oxygen demand

EC electrical conductivity

F correction factor for the ratio $f_{gt\ ij}$

$f_{gt\ ij}$ ratio of wastewater production red/white

FW Farm Winery

gt_j ratio of grape type, red/white, (%)

i Periods ($i = 1$, Period I; $i = 2$, Period II)

j type of grape ($j = 1$, white wine; $j = 2$, red wine)

NTU Nomenclature Territorial Units

P production (kg of grape/yr)

Q_i ratio of wastewater flow in each Period (%)

$Q_{i,j}$ average wastewater flow (m^3/d)

T number of days of each Period

TSS total suspended solids

V vinification rate

W annual wastewater produced (m^3/yr)

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INTRODUCTION

The context of the Mediterranean wine industry

The global wine industry assumes considerable relevance in Europe, particularly in Mediterranean countries such as Portugal (IVV 2016). Climate change affects water resources worldwide and Southern Europe is one of the regions where water scarcity is expected to increase in the future (Lavrić *et al.* 2017), which represents a risk for the wine sector (Fraga *et al.* 2018). Furthermore, wine consumers are increasingly aware of the environmental impact of the sector (Costa *et al.* 2016; Martins *et al.* 2018). Therefore, new strategies to save water in the vineyards and wineries are required and the use of alternative water resources is increasingly considered in dry areas (EC 2012). In this context, the environmental impact of viticulture and oenology demands improved characterization to support the efforts of the modern wine industry to adapt to climate change, minimize environmental burdens and guarantee consumer acceptance (Christ & Burritt 2013; Martins *et al.* 2018).

Portugal has 14 different winegrowing regions. However, according to Nomenclature Territorial Units 2 (NTU2) they are aggregated in only seven regions, and the Alentejo NTU2 region includes the Alentejo and Tejo winegrowing regions. In Alentejo, the average area per farm is about 6.8 ha, which is five times that of the country's average, accounting for 20% of the Portuguese wine-production area and about one-third of Portuguese wine production (IVV 2016).

The climate of the Alentejo NTU2 region has an average temperature of 14.5 °C with maximum average values of 33 °C (July–August) and minimum values of 5 °C or less (in January), and 3,000 h/yr of sun. Temperatures can be colder in winter and heat waves can strike during summer and the region is characterized by large inter-annual variability in terms of precipitation (Figure 1).

About 50% of the Alentejo NTU2 vineyards are already irrigated (IVV 2016). Therefore, one of the biggest challenges for the Portuguese wine industry relates to water issues, namely water use, wastewater production and management in viticulture and oenology (Peth *et al.* 2017). In a climate change scenario that predicts restrictions in water availability in dry areas for the industry and irrigated agriculture, and where additional gains in water use

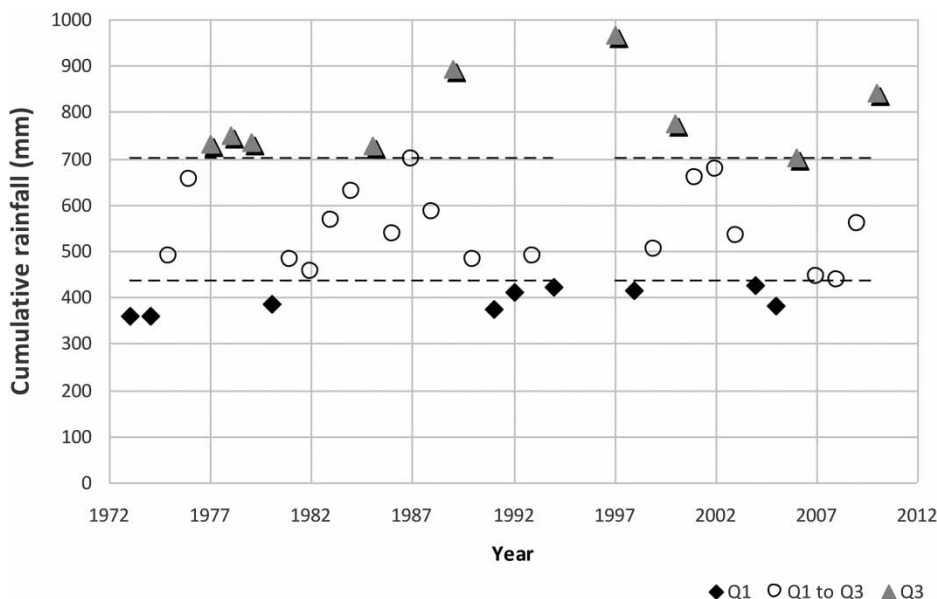


Figure 1 | Yearly accumulated rainfall variability for Évora (AlentejoNTU2) over the period comprising 1973–2010. Q1 to Q3 represents the interquartile range, and shows the variability of the middle 50% yearly accumulated rainfall events observed in that period of observation. Q1 (first quartile rank) represents the lowest 25% yearly accumulated rainfall events in the analyzed period. Q3 (third quartile rank) refers to the highest 25% yearly accumulated rainfall events in the analyzed period (Source: adapted Coelho *et al.* 2013).

efficiency are difficult to achieve, water reuse for multiple purposes can be an alternative solution for the wine sector. Moreover, implementation of leading practices for sustainable water and wastewater management in the wine sector will help to protect water resources.

Water issues related to wine production in the Mediterranean

Similarly to other industries, winemaking can create a negative environmental impact that must be minimized (Navarro *et al.* 2017). The fact that industrial processes and production methods related to wine production are largely dependent on the type of operation and organized along the wine-growing phase (viticulture), winemaking phase (oenology) or a combination of both (viticulture–oenology) pressures the industry to face a complex mixture of, often interconnected, environmental issues, restrictions and problems (Costa *et al.* 2016; Martins *et al.* 2018).

One of the most important issues in the Mediterranean area concerns water metrics and sustainable water use in both the farm and the winery. In the case of the winemaking phase, water-use assessment must consider the different vinification stages (i.e., preliminary phases, fermentation, wine clarification, cleaning and bottling) in order to identify hotspots and provide potential solutions to improve environmental performance (e.g. water savings, decreased water pollution, water reuse).

It is well reported in previous literature that water use at the winery depends on several characteristics, namely the winery dimension, the type of wine (e.g. red, white or special wines) and the available cleaning and winemaking technologies (Brito *et al.* 2007; GWRDC 2011; Oliveira & Duarte 2016). This may justify to a great extent why water use (e.g. L of water/L of wine produced) can vary widely with the region, company and country (Kumar & Christen 2009; Oliveira & Duarte 2015). Australian wineries still use over 8 L of water in the winery to produce a bottle of wine (750 mL) despite the reported best practice of 0.4 L referred to in the literature (Kumar & Christen 2009). However, our own previous findings show that the water volume consumed is proportional to vintage duration, i.e. a longer harvesting period leads to higher water consumption (Oliveira & Duarte 2015). In addition, the larger wineries often have

more efficient use of water resources and a smaller specific volume of wastewater requiring disposal and/or treatment and show better data reporting than smaller ones. Wineries often produce large amounts of wastewater and the seasonal nature of the winemaking industry poses problems for wastewater treatment in terms of volume and composition. Therefore, the sector is increasingly demanding efficient and low-cost alternatives based on the concept of ‘fit for purpose’ wastewater treatment to treat winery wastewater and promote planned discharge or recycling (GWRDC 2011).

Water use in the vineyard, but also in the winery, is not well characterized for the Portuguese reality (Costa *et al.* 2016). More detailed quantification is required attending to water scarcity problems and the increasing restrictions posed to industrial water users. Water use in the winery relates mainly to the cleaning of equipment, tanks, vats, barrels, presses, de-stemmers, reception hoods and taps, floors, walls and pipes (Andreottola *et al.* 2009; Oliveira & Duarte 2015). Moreover, water use depends on the type and size of the winery and the type of wine (red, white, others) and technology (Brito *et al.* 2007; Andreottola *et al.* 2009; GWRDC 2011). Considering this scenario, a simplified approach based on the previous work of Duarte *et al.* (2004) and Oliveira & Duarte (2016) is proposed in which two or more activities are aggregated. The Portuguese wine industry is largely based on small and small-medium sized wineries (Table 1), so a ‘Farm Winery’ (FW) concept can integrate the majority of Portuguese viticulture and oenology producers, where vineyard and wine production are considered as a single-stream grape system. Most of the wine producers of the Alentejo NTU2 region correspond to small-medium and medium sized integrating the concept of FW, accounting for 27% of national wine production (IVV 2016).

Metrics and indicators in the wine industry

The wine industry requires improved water metrics in order to robustly evaluate and predict its sustainability and environmental impact. Indeed, several sustainability programs for wine chain production have emerged worldwide, and in particular in the ‘New World’ producing countries such as the USA, New Zealand or Australia. These programs aim to address the increasing need for evaluation and scrutiny by stakeholders (government, customers and consumers)

Table 1 | Winery types in Portugal, according to the wine volume production capacity (IVV 2016)

Code	Winery class (hL/yr)	Number of wineries	Wine production (hL)	% Wineries	% Wine production
Small	<2,000	20,884	919,380	98.1	15.4
Small/Medium	2,000–5,000	196	608,940	0.9	10.2
Medium	5,000–10,000	82	549,240	0.4	9.2
Large	>10,000	120	3,892,440	0.6	65.2
Total		21,282	5,970,000	100	100

on the environmental performance of the wine industry (Gemmrich & Arnold 2007; Martins *et al.* 2018). In addition, audit firms for benchmarking and environmental performance of water issues require more accurate monitoring of water use and wastewater production (EPA 2004) and more consistent standards/metrics for sustainability, regardless of the ‘terroir,’ region and management practices.

Global indicators for wastewater production were proposed as a function of grapes crushed or wine produced (Sheridan *et al.* 2005; Aybar *et al.* 2007). Multiple key indicators were used to assess the sustainability of the wine industry. However, results vary with the region/country, the size of the winery or even with the type of grape and related winemaking technology, which makes it complicated for stakeholders or auditors to compare ‘companies/farms’ performance (Da Ros *et al.* 2017). Indeed, there is still a lack of information in relation to dedicated indicators, which should combine BAT implementation, size of the winery, different winemaking periods and also final disposal/reuse practices. In this context, the aim of the study is to propose an integrative approach for wine production in the Alentejo NTU2 and develop a simple calculation model for water use and wastewater production in the winery, as a function of winemaking aggregated periods and type of processed grapes. The model was applied to FW case studies located in the Alentejo NTU2 region.

MATERIALS AND METHODOLOGY

Case studies characterization

The present study was carried out in Portugal, particularly in the NTU2 of Alentejo, which comprises the Alentejo

and Tejo winegrowing regions. Winery I and Winery II were selected on the basis of the conceptual approach of FW systems, in order to evaluate an integrated strategy of vineyard and winery on water issues. These two medium sized wineries (5,000–10,000 hL production capacity) were monitored during three campaigns, between August 2013 and July 2016. With this purpose the winery installed water flow meters to provide daily registers. It is assumed that all the water consumed is discharged as wastewater.

Sampling approach

In order to optimize the analysis, a simplified approach was considered as previously proposed by Duarte *et al.* (2004) and Oliveira & Duarte (2016). Two or more activities were aggregated: (1) vintage and first racking (Period I) characterized by high peak flows and high pollution loads; and (2) all the remaining activities, including bottling (Period II) characterized by reduced water flows and medium/low pollution loads (Figure 2). During Period I, the flows and loads were analyzed weekly; during Period II samples were collected twice a month.

Wastewater production and characterization

Composite samples of the winery wastewater, representative of each phase of the process, were taken and kept at 4 °C. Several key parameters were analyzed, according to the Standard Methods (APHA 2012), to assess winery wastewater load (Table 2): pH, electrical conductivity (EC), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS) and total polyphenols.

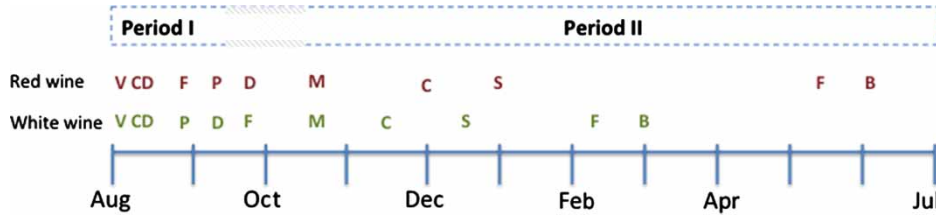


Figure 2 | Winemaking timeline for the winery, as function of the type of wine (red or white). V – vintage; CD – crushing/destemming; F – filtration; P – pressing; D – decanting; M – maturation; C – clarification; S – stabilization; B – bottling.

Table 2 | Wastewater characterization according to the working period

Parameters	Period I		Period II
	White	Red	
BOD ₅ (g O ₂ /L)	1.0–1.1	1.3–4.9	0.25–8.6
COD (g O ₂ /L)	2.2–5.4	2.5–10.1	2.8–17.0
Polyphenols (mg/L)	10.0–12.9	28.0–54.0	18.0–270
TSS (g/L)	0.3–1.6	0.9–3.6	0.10–4.9
EC (μS/cm)	460–1,400	740–1,400	920–3,200
pH	5.6–6.0	4.1–6.2	3.5–11.5

Calculation model

A calculation model is proposed to determine a ‘Global Indicator’ of wastewater production based on ‘Dedicated Indicators’ of water consumption (Equation (1)). If different periods and type of wine produced are considered as well as the implementation of best available technics (BAT), it is possible to calculate the Dedicated Indicators, based on labour periods (Equation (2) and Equation (3)). Wineries that apply BAT can reduce wastewater production 30–50%. During Period I white wine can produce less wastewater than red. Therefore, the ratio of wastewater production red/white ($f_{gt\ ij}$) considers this information. During Period II the activities are measured together, so F is the correction factor for the ratio $f_{gt\ ij}$ during Period II and $f_{gt\ 2j}$ is then $1/F$.

$$\begin{aligned} \text{Global Indicator } (L_{\text{wastewater}}/L_{\text{wine}}) \\ = \sum \text{Dedicated Indicators} \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Global Indicator } (L_{\text{wastewater}}/L_{\text{wine}}) \\ = \frac{1}{PV} \left[\sum_{i=1}^n W Q_i F \sum_{j=1}^m g_{tj} f_{gt\ ij} \right] BAT \end{aligned} \quad (2)$$

$$F = \frac{1}{\sum_{j=1}^m \%gt_j F_{gt\ ij}} \quad (3)$$

where,

i – Periods ($i = 1$, Period I; $i = 2$, Period II)

j – type of grape ($j = 1$, white wine; $j = 2$, red wine)

P – production (kg of grape/yr)

V – vinification rate

Q_i – ratio of wastewater flow in each Period (%)

W – annual wastewater produced (m³/yr)

g_{tj} – ratio of grape type, red/white, (%)

$f_{gt\ ij}$ – ratio of wastewater production red/white

F – correction factor for the ratio $f_{gt\ ij}$ during Period II

BAT – coefficient related to BATs implementation.

If the interest is the assessment of Dedicated Indicators, based on type of wine, Equation (2) can be modified to Equation (4), and the dedicated indicator will be expressed as $L_{\text{wastewater}}/L_{\text{white wine}}$ OR $L_{\text{wastewater}}/L_{\text{red wine}}$.

$$\begin{aligned} \text{Global Indicator } (L_{\text{wastewater}}/L_{\text{wine}}) \\ = \frac{1}{PV} \left[\sum_{j=1}^m W F g_{tj} \sum_{i=1}^n Q_i f_{gt\ ij} \right] BAT \end{aligned} \quad (4)$$

On the other hand, if all flows are known, in both periods, as well as the length of each Period I and II, Equation (2) can be simplified as Equation (5):

$$\begin{aligned} \text{Global Indicator } (L_{\text{wastewater}}/L_{\text{wine}}) \\ = \frac{1}{PV} \left[\sum_{i=1}^n \sum_{j=1}^m \bar{Q}_{ij} T_{ij} \right] BAT \end{aligned} \quad (5)$$

where,

i – Periods ($i = 1$, Period I; $i = 2$, Period II)

j – type of grape ($j = 1$, white wine; $j = 2$, red wine)

P – production (kg of grape/yr)

V – vinification rate

$Q_{i,j}$ – average wastewater flow (m^3/d)

t – number of days of each Period

BAT – coefficient related to BATs implementation.

Data collection, of each representative vinification process, obtained in previous Portuguese case studies (FW) was grouped (Table 3) and can be used as reference values to fill the model for wineries where there is lack of information.

RESULTS AND DISCUSSION

There are several references for the amount of wastewater produced per litre of wine bottled ($L_{\text{wastewater}}/L_{\text{wine}}$) but wastewater production as a function of the type of grape (white versus red) has not been fully addressed. The proposed approach allows the stakeholder to evaluate wastewater production throughout the year, by labour period and by type of grape processed, based on their own parameters: production (kg grape/yr); vinification rate, usually 0.75; type of grape processed (white or red) and annual water consumption during the oenological processes (Table 4).

A more integrated approach of vineyard and winery environmental management is required by the modern wine industry. To optimize the system, the focus should be on the knowledge of flows and loads, during Periods I and II, according to dimension and type of grape processed

(white vs red). In this study it is not only possible to analyse the global indicator of water consumption, but also to identify dedicated indicators, as a function of processed grapes or labour period (Table 5). In the present study, two wineries were monitored for water consumption and a ratio of 2.2 ± 0.45 and 2.1 ± 0.17 L of water/L of wine was recorded. These values are in agreement with the range most frequently reported by other authors, 2–3 L of water/L of wine (Bolzonella & Rosso 2009). Usually, the variation of this ratio is related to the amount of grapes processed, and different models have been proposed to predict a global indicator of wastewater generated, as a function of the amount of grapes crushed or wine produced. For example, Aybar et al. (2007) correlated wastewater generated (V) and grapes produced by the equation $V = 226P^{-0.315}$, where P is grape production, whereas Sheridan et al. (2005) proposed the equation $A = 4037.5T^{0.9243}$ to estimate the water consumption (A), based on ton of processed grapes (T). Nevertheless, when these equations were applied to the Portuguese case-studies an overestimation of the wastewater produced was found. Also, it was identified that in small to medium sized wineries, years of lower production affected negatively the water ratio consumption. This could be explained by some specific washing operations which are strongly dependent on the size of the tanks, e.g. fermentation vessels, storage tanks and maturation tanks (Vlyssides et al. 2005), because regardless of the amount of grapes processed, the tanks and machinery have a fixed volume or size and consume the same amount of washing water.

Regarding wastewater distribution throughout the year, our data revealed that most of the wastewater (60–75%) was produced during Period I (vintage and first racking periods), which lasts one to two months. In addition, in Italy, 78% of the global wastewater produced was generated during this winemaking period (Lofrano et al. 2009). As the quantity of red wine produced in Portugal is globally higher, the water consumption related to red wine production is higher. Furthermore, the results show that red wine leads to more water consumption related to waste removal, presenting an increase of 50–64% of water consumption compared with white wine, regardless of the amount of wine produced.

These findings highlight that the wastewater treatment system should be flexible, capable of facing fluctuations of

Table 3 | Global and dedicated indicators for wastewater flows in Portuguese wineries, according to the working period

		Winery type Medium	
	Type of grape $L_{\text{water}}/L_{\text{wine}}$	White 1–2	Red 2–3
Period I (30–60 d)	Wastewater ratio $f_{gt\ 1j}$	0.6–0.8 1	1–4
Period II (305–335 d)	Wastewater ratio $f_{gt\ 2j}$	0.2–0.4 $1/F$	
With BAT		0.5–0.7	

Table 4 | Data collected in the case studies during three years of monitoring

	yr	P (m ³ /yr)	W (m ³ /yr)	Q ₁	gt ₂	f _{gt11}	f _{gt12}	F	BAT
Winery I	1	585	1,540	0.73	0.70	1	2	0.588	+
	2	820	1,420	0.70	0.65	1	2	0.606	+
	3	695	1,570	0.65	0.65	1	2	0.606	+
Average		700	1,510	0.69	0.67	1	2	0.600	+
Winery II	1	570	1,215	0.70	0.60	1	3	0.455	+
	2	760	1,430	0.68	0.60	1	3	0.455	+
	3	620	1,370	0.60	0.58	1	3	0.463	+
Average		650	1,340	0.63	0.59	1	3	0.457	+

Table 5 | Model application to the medium sized wineries (Winery I and Winery II) located in the dry region of Alentejo NUT2, south Portugal

	Year	Global Indicator (L _{water} /L _{wine})	Dedicated Indicator (L _{water} /L _{white wine})	Dedicated Indicator (L _{water} /L _{red wine})	% ww red wine	Dedicated Indicator (L _{water} /L _{wine Pi})	Dedicated Indicator (L _{water} /L _{wine PII})
Winery I	1	2.6	1.8	3.0	79	1.9	0.7
	2	1.7	1.2	2.0	75	1.2	0.5
	3	2.3	1.7	2.6	74	1.5	0.8
Average		2.2	1.6	2.5	76	1.5	0.7
Winery II	1	2.1	1.3	2.7	75	1.5	0.6
	2	1.9	1.2	2.3	75	1.3	0.6
	3	2.1	1.5	2.7	72	1.3	0.9
Average		2.1	1.3	2.6	74	1.4	0.7

volumes and loads, and allow adequate removal yields accordingly to final purpose. This calculation model will be able to produce an environmental diagnosis for FW case studies, in order to improve wastewater management and minimize errors in the design/operation of the treatment system.

Water is becoming scarce, particularly in dry regions. Treated wastewater can thus emerge as an alternative water resource. In Europe, the requirements for treated wastewater reuse in irrigation mainly include microbiological parameters, since its main focus is the reuse of domestic wastewater (Brissaud 2008). In Portugal, the legislation (DL n° 236/98, Annex XVI) provides water quality standards for irrigation, based on some physical-chemical parameters and two microbiological parameters (faecal coliforms and eggs of intestinal parasites). However, this legislation is not specific for reuse of treated wastewater, and the indicator parameters of organic matter, such as COD or BOD, are not covered. To regulate the use of treated wastewater in irrigation, a Portuguese Standard was

published in 2005 (NP 4434) but this standard refers, only, to the reuse of domestic wastewater, stipulating four quality classes based on microbiological parameters. In this sense, the wastewaters, without faecal microorganisms but containing other contaminants, are not properly regulated. Moreover, the potential risks of phytotoxicity associated with this type of wastewater (Oliveira *et al.* 2009; Mosse *et al.* 2010) and the role of the edapho-climatic conditions of the winegrowing region should be better studied to create/adapt guidelines that are in compliance with the local legal requirements, as established in countries with high environmental concerns (EPA 2004; Mekala *et al.* 2008) and also to avoid the negative environmental impact related to the use of treated wastewater.

CONCLUSIONS

This methodology and related modelling approach have the major advantages of flexibility and adaptation to different

case studies. This way, each type of winery will be able to develop its own sustainable indicators allowing benchmarking with similar wineries and to compare performances. This calculation model could be an advantage in wastewater management, particularly in Mediterranean dry areas where the demand for new water resources is identified as one of the most prominent hotspots in future climate-change projections for the Mediterranean basin. This approach towards the ultimate goal of ‘closing the cycle’ by reusing treated industrial wastewater onsite plays a key role in wine production water management.

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