Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1029532

57 (2016) 8670–8682
April

Reuse of wastewater: a feasible option, or not? A decision support system can solve the doubt

M. Papa[a,1], G. Bertanza[a,*,1], A. Abbà[b]

[a]*Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, via Branze 43, I-25123 Brescia, Italy, Tel. +39 030 371 1301; Fax: +39 030 371 1312; emails: matteo.papa@unibs.it (M. Papa), giorgio.bertanza@unibs.it (G. Bertanza)*

[b]*Department of Civil Engineering and Architecture, University of Pavia, via Ferrata 3, 27100 Pavia, Italy, Tel. +39 0382 985 312; email: abba78@unipv.it*

Received 9 October 2014; Accepted 1 March 2015

ABSTRACT

A wide debate on wastewater reuse has been turning on within the scientific community (and also at the legislative level) for several years. Beyond the undeniable advantages linked to the recovery of a material resource, the typical question plaguing water managers sounds like: "Is this practice feasible, in terms of both technical and economic sustainability?". To answer their query, we have developed an innovative tool that rates the three actors of the reclamation process (the wastewater treatment plant WWTP, the hydraulic system, and the final user) by means of a waterfall framework based on the following: (i) the definition of meaningful input factors, (ii) the calculation of robust indices, and (iii) the synthesis process up to a final evaluation (numerical values). The model has been successfully applied to several case studies, where the reuse is either already practiced or under study: As a result, the most suitable scenario for reuse (i.e. #1 WWTP), together with the main opportunities (e.g. a crucial increase in water availability for the final user: #1 WWTP) and threats (e.g. the worst quality of the effluent compared to the current source) has been identified. In summary, this tool represents a useful technical support for decision-makers whenever a judgment on reuse feasibility is required.

Keywords: Decision support systems; Experimental validation; Indices; Wastewater reuse; Water availability

1. Introduction

Water resources are currently subject to strong pressures caused by the awareness that water is a limited resource [1], and cities around the world are facing complex water management dilemmas [2]. Water scarcity is increasingly threatening Europe and mainly the Mediterranean basin [1]: The water stress index, representing the ratio of a country's total water withdrawal to its total renewable freshwater resources, highlights a severe imbalance in water demand and supply in southern Europe [3].

The possibility to decrease freshwater harvest while increasing water supply by using treated

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*Corresponding author.

[1] These authors are equally contributed to the work.

wastewater can help to face these challenges: Indeed, water scarcity is strictly related with wastewater abundance, as sewage amount is likely to significantly rise with population growth, rapid urbanization, and improvement of sanitation service coverage [4]. Reuse practices are well documented in scientific literature (as reported, in case of agricultural reclamation, in the review [5]), and a realistic estimation confirms that 20 million hectares in the world are irrigated by raw, treated, and/or partially diluted wastewater [6].

Nevertheless, despite its great opportunities, a full development of reuse is currently hampered by 2 constrains:

- On the technical side, finishing treatments, such as membrane ([7–9]) or tertiary filtration [10], are often necessary to satisfy quality criteria: Salinity, pathogens, nutrients, and heavy metals represent the main critical parameters to be controlled in case of agricultural reuse (see, for instance, the regulations in force in Italy: Decree of the Italian Environmental Ministry, M.D. 185/2003, reported in S1 of Supporting Information).
- On the economic side, an increase of the costs (either for plant upgrade, water distribution system, and the monitoring of the whole reuse system) cannot be avoided.

For these reasons, wastewater reuse feasibility can be fully assessed only by means of a technical-economic tool, able to perform integrated evaluations at a large scale (e.g. a basin-scale, characterized by a high degree of complexity); on the contrary, the lack of reliable and science-based evaluation criteria leads decision-makers to keep conservative positions (i.e. forbidden reuse), on the basis of personal opinions, views, and/or experiences [11], or for the scarce social acceptance due to a perceived risk to human health [12].

Several methods have been proposed for the assessment of wastewater reuse suitability, focusing on different topics. Hidalgo et al. [13] proposed a multicriteria (MC) software with a quick evaluation of unit process design, alternative schemes, and possible final uses: Considered items were land availability, type of soil, type of crops, water requirement, and meteorological conditions. Verlicchi et al. [14] proposed an index (WWPI, wastewater polishing index) comparing the water quality level achieved by different sequences of polishing treatments, on the basis of a set of parameters (BOD_5, COD, TSS, P_{tot}, NH_4^+, and *E. coli*), and its proximity to law thresholds for reuse. Iglesias et al. [15] analyzed the economic impacts of finishing treatments and determined the costs of appropriate treatment trains for different reuse purposes. Lavee [16] focused on farmers' choice of crops, as a consequence of freshwater supply uncertainty: When the costs associated with the lost profits were considered, the construction of wastewater treatment facilities for the use in agricultural irrigation was found to be economically worthwhile. Alcon et al. [17] demonstrated how the non-market benefits of the use of wastewater in agricultural irrigation could provide an economic justification to the additional treatment costs. MC analyses were performed to determine the net benefit of using treated wastewater to irrigate crops in the Gaza Strip of Palestine [18], showing great savings for farmers. All these works show how MC-like analyses were found to be extremely suitable, as more accurate as greater the amount of available information [12].

For this reason, we have developed a decision support system (DSS) for the evaluation of wastewater reuse feasibility; a large set of input factors is assessed, not only the compliance with target thresholds, related to each "actor" of the reclamation process:

(1) the wastewater treatment plant (WWTP);
(2) the hydraulic system, required to transport water from the plant to the user;
(3) the final user (e.g. crops irrigation).

It is the goal of this paper, first of all, to present and describe the DSS (selection of parameters and relative weights, rating curves, aggregation function, etc.). Then, two examples of the application of the whole procedure to real case studies are presented, in order to elucidate how the DSS can be adopted in the decision-making process.

2. Materials and methods: description of the assessment procedure

The proposed DSS is aimed at judging the feasibility of wastewater reuse, and it is founded on an integrated assessment of the entire "reuse chain"; a synthetic index is finally reached, that is, a unit-less number representing the suitability of the studied situation to implement reuse. Each actor is firstly analyzed separately, in order to reach a good level of knowledge of each part; then, the techno-economic findings are synthesized in an overall judgment.

The procedure is based on a waterfall step (graphically represented in Fig. 1). As starting point, an aggregate set of technical and economic parameters (namely "input factors") is defined; they must describe the actors of the process: for example, for a WWTP, the influent and the effluent concentrations of a given parameter. According to [19], index scores (namely "indices") are assigned to each factor by comparing its measurement with target values (typically, in the case of WWTP, the normative standard), by means of normalization/rating curves. Eventually, indices, optionally weighted, are combined into the final evaluation: This is a fundamental step, in order to obtain a rapid and prompt answer for decision-makers [14]. Procedure details are described in the following sections.

2.1. The input factors

Table 1 (top) lists the factors that we propose for the WWTP, the hydraulic system, and the final user, respectively. Their choice was addressed by the following considerations:

- *WWTP*. In this case, DSS input factors are represented by the chemical, physical, and microbiological parameters, chosen according to the final destination of reused wastewater. For instance, for agricultural reclamation, either the parameters reported by local regulations (if present: in Italy, M.D. 185/2003) or only a proper set can be considered. In this work, 7 key parameters (BOD_5, COD, NH_4^+, N_{tot}, P_{tot}, TSS, and *E. coli*, as also suggested by Verlicchi et al. [14]) were selected as basic scenario for the assessment; moreover, an additional (deeper) analysis can be also carried out, if more information is available (see Table 1—bottom—for the list of supplemental data); they can take into account: (i) from the one side, the statistical distribution of input factors (if, e.g. daily concentrations of key parameters are available), in order to guarantee data robustness; (ii) from the other side, other useful (but rarely monitored) parameters (e.g. SAR, sodium adsorption ratio, and EC, electrical conductivity). In this case, the DSS can modify its outcomes, depending on the number of added parameters (see S2 of Supporting Information reporting the indices of #1 WWTP with additional data).

  In case additional treatments for effluent polishing are required (i.e. a disinfection stage), capital and operating costs are accounted for in the economic factors of the hydraulic system.

- *Hydraulic system*. Water transportation from the WWTP to the user is a costly step related to both the quantity of water supplied and the distance to the final users. As a consequence, this actor is the *lieu* of the economic comparison: from the one side, the (eventual) post-treatment for effluent polishing (for the WWTP) and the delivery of treated wastewater to the final user (for the hydraulic system), and from the other side, the current freshwater source (for the final user), as reported in Table 1 (top). Also in this case, the detailed parameters of

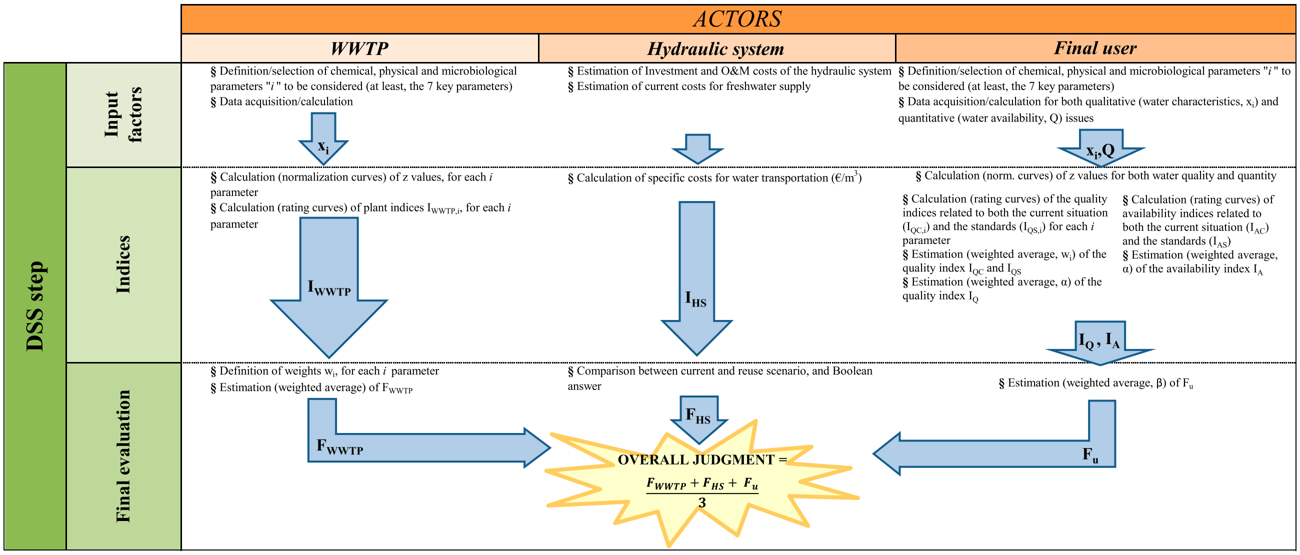

Fig. 1. DSS conceptual framework: Flow-sheet diagram summarizing main steps and outcomes. Arrows represent the outputs of each step, ending with the determination of the final overall judgment.

Table 1
Top: list of input factors used in the case studies (for the final user, the case of agricultural reuse is reported); the subscript "i" represents a physical, chemical, or microbiological parameter (at least, the 7 key parameters). Bottom: overall description of the parameters (both minimum level of knowledge and supplementary information) to be used in the DSS

	DSS input factors	U.M.	Symbol
WWTP	WWTP inlet concentration		$x_{i,IN}$
	WWTP outlet concentration		$x_{i,EFF}$
	Legal limit to be complied with		$x_{i,LIM}$
Hydraulic system	Investment (depreciation) costs	€/y	C_I
	Operation and maintenance costs	€/y	$C_{O\&M}$
	Costs of current (fresh)water source	€/y	C_C
Final user (e.g. agricultural reuse)	Current water availability	m^3/d	Q_C
	Water requirements for crops	m^3/d	Q_{MIN}
	WWTP effluent flow rate potentially subject to reuse	m^3/d	Q_R
	Flow rate of the current supply source that would be used also under reuse hypothesis	m^3/d	Q'_C
	Concentration in the current (fresh)water source		$x_{i,C}$
	Concentration under reuse hypothesis		$x_{i,R}$
	Maximum allowable concentration		$x_{i,MAX}$

	Minimum level of knowledge	Supplementary data
WWTP	Treated and reused (if practiced) flow rate (typical value for dry weather conditions) Typical influent and effluent concentrations of the following 7 key parameters: BOD_5, COD, NH_4^+, N_{tot}, P_{tot}, TSS, and *E. coli*	Daily flow rate values (over one year) Daily concentrations (over one year) for 7 key- parameters Typical influent and effluent concentrations of other relevant parameters, according to reuse purpose (e.g. sodium adsorption ratio, SAR, and electrical conductivity, EC, for agricultural reuse)
Hydraulic system	Costs estimation (Investment and O&M) for required infrastructures/additional treatments Funding programs/agreements for infrastructures Current cost for (fresh)water supply	Detailed features for required infrastructures: maximum flow rate to be conveyed (m^3/s); pipe length (m); available load (m); inclination (m/m); geodetic head (m); pipe diameter (m); accumulation basin (m^3); investment cost (€); depreciation rate (€/y); pumping energy (kWh/m^3); electric energy cost (€/y); maintenance cost (€/y)
Final user (e.g. agricultural reuse)	Water requirements (daily flow rate and length) Current (fresh)water source: availability and characteristics Water quality standards to be complied with Dilution ratio (reused wastewater/current (fresh)water source)	Detailed description of reuse scenario: for example, in case of agricultural reclamation, type of crops, their extension, etc.

infrastructures such as energy requirement for a new treatment or pipe length (supplementary data in Table 1—bottom), instead of an estimation of the costs (investment, *I*, and operation and maintenance, O&M), can increase the strength of this economic assessment.

- *Final user*. Water quality and availability are the milestones for this stage: Factors are then related to these aspects. In Table 1, as an example, we have shown the ones suitable for agricultural reuse, either estimated, or, if supplementary parameters are available, calculated starting from the detailed description of reuse scenario (type of crops, soil properties, etc.). Likewise, other factors can be elaborated for other types of reclamation (both civil and industrial: e.g. cooling, washing, and other process waters).

2.2. The indices

Once DSS input factors have been acquired and/or calculated, their values (with heterogeneous units, depending on the specific parameter) are transformed in comparable indices with uniform variability ranges, by means of appropriate normalization (z) and rating (I) curves; these functions have been defined assuming the following key points:

(1) Actual conditions (e.g. WWTP effluent concentration of a given parameter) are compared with standard reference values, for example, limits for reuse (*normalization step*);
(2) the more the system is far from neutral conditions, the stronger is the positivity/negativity of judgment, I (*rating step*): Calculated score varies from +1 (best case) to −1 (worst case), and a positive ranking denotes a favorable situation (e.g. WWTP effluent concentration lower than the standard to be complied with).

In particular, we propose a polynomial function as rating curve (Eq. (1)), equal for each actor:

$$I = \tilde{F}(z) = \begin{cases} a \cdot (z-1)^n, & |-1 < \tilde{F}(z) < 1 \\ +1, & |\tilde{F}(z) \geq 1 \\ -1, & |\tilde{F}(z) \leq -1 \end{cases} \tag{1}$$

where

- z are the normalized values: Mathematical definitions are summarized in Table 2, and in detail explained for each actor in the following paragraphs;
- a (<0) and n (which represents the polynomial degree: If n takes even values, then $|a|$ must be used for $z < 1$) are the rating curves parameters that can be freely selected for each assessed scenario; in this work, we adopted $a = -1.5$ and $n = 2$ (quadratic function).

In Fig. 2(a), the graphical representation of Eq. (1) is shown for the current scenario; similarly, S4 of Supporting Information displays other possible functions: (i) a straight line as suggested by Verlicchi et al. [14], that is, Eq. (1) with $a = -1$ and $n = 1$, (ii) a cubic ($n = 3$), and (iii) a hyperbolic-like function.

As far as the economic aspects are concerned, as previously stated, they are accounted for in the evaluation of water conveying costs, so that Eq. (1) has not to be applied.

2.2.1. WWTP

For each considered parameter “i,” the WWTP index I_{WWTP} can be calculated according to Eq. (1), with z values deriving from the effluent concentration normalized toward the limit (curves shown in Table 2 and Fig. 2(b): If the effluent exceeds the limit, the mathematical formulation incorporates also the influent concentration as a variable for the judgment.

As a further analysis, if a large number of measurements are available, indices can be calculated also with concentrations other than the typical value: For example, we suggest the 75th and the 95th percentile, and the maximum value of effluent concentration for the 7 key parameters: In this way, additional information on plant reliability can be obtained.

2.2.2. Hydraulic system (economic comparison)

As previously stated, the costs for additional treatments of WWTP effluent for final polishing and the costs for the hydraulic system are calculated (in terms of I and O&M costs) and compared with the costs of the water currently used.

The numerical value of this index (I_{HS}) is then expressed as €/m^3, and it represents the overall economic index of the procedure.

2.2.3. Final user

Final user indices should reflect the (possible) benefits of using wastewater for reuse purposes. To reach this aim, 2 items must be considered: (i) the quality (Q) of waste- and freshwaters (i.e. their chemical, physical, and microbiological characteristics)

Table 2
Normalization and rating curves for final evaluation determination. Again, the subscript "i" indicates that an index has to be calculated for the *i*th (physical, chemical, or microbiological) parameter

Actor	z calculation: normalization curves	Indices calculation: rating curves			Final evaluation
WWTP	$z = f(x) = \begin{cases} \frac{x_{\mathrm{EFF}}}{x_{\mathrm{LIM}}}, \lvert x_{\mathrm{EFF}} \le x_{\mathrm{LIM}} \\ \frac{x_{\mathrm{EFF}}+x_{\mathrm{IN}}-2\cdot x_{\mathrm{LIM}}}{x_{IN}-x_{\mathrm{LIM}}}, \lvert x_{\mathrm{EFF}} > x_{\mathrm{LIM}} \end{cases}$	$I_{\mathrm{WWTP,i}} = \tilde{F}(\mathrm{z})$			$F_{\mathrm{WWTP}} = \sum I_{\mathrm{WWTP,i}} \cdot w_{\mathrm{i}}$
Final user	$z = f(x) = \begin{cases} \frac{x_{\mathrm{R}}}{x_{\mathrm{C}}}, \lvert x_{\mathrm{R}} \le x_{\mathrm{C}} \\ \frac{x_{\mathrm{R}}+8\cdot x_{\mathrm{C}}}{9\cdot x_{\mathrm{C}}}, \lvert x_{\mathrm{R}} > x_{\mathrm{C}} \\ \frac{x_{\mathrm{C}}}{x_{\mathrm{R}}}, \lvert Q'_{\mathrm{C}} = 0^{*} \end{cases}$	$I_{\mathrm{QC,i}} = \begin{cases} \tilde{F}(z), \lvert Q\prime_{\mathrm{C}} \neq 0 \\ -\tilde{F}(z), \lvert Q\prime_{\mathrm{C}} = 0 \end{cases}$	$I_{\mathrm{QC}} = \sum I_{\mathrm{QC,i}} \cdot w_{\mathrm{i}}$	$I_{\mathrm{Q}} = I_{\mathrm{QC}} \cdot \alpha + I_{\mathrm{QS}} \cdot (1-\alpha)$	$F_{\mathrm{u}} = I_{\mathrm{Q}} \cdot \beta + I_{\mathrm{A}} \cdot (1-\beta)$
	$z = f(x) \begin{cases} \frac{x_{\mathrm{R}}}{x_{\mathrm{MAX}}}, \lvert x_{\mathrm{R}} \le x_{\mathrm{MAX}} \\ \frac{x_{EFF}+x_{\mathrm{R}}-2\cdot x_{\mathrm{MAX}}}{x_{\mathrm{EFF}}-x_{\mathrm{MAX}}}, \lvert x_{\mathrm{R}} > x_{\mathrm{MAX}} \cup x_{\mathrm{C}} \le x_{\mathrm{EFF}} \\ \frac{x_{\mathrm{C}}+x_{\mathrm{R}}-2\cdot x_{\mathrm{MAX}}}{x_{\mathrm{C}}-x_{\mathrm{MAX}}}, \lvert x_{\mathrm{R}} > x_{\mathrm{MAX}} \cup x_{\mathrm{C}} > x_{\mathrm{EFF}} \end{cases}$	$I_{\mathrm{QS,i}} = \tilde{F}(\mathrm{z})$	$I_{\mathrm{QS}} = \sum I_{\mathrm{QS,i}} \cdot w_{\mathrm{i}}$		
	$z = f(Q) = \frac{Q_{\mathrm{C}}}{Q'_{\mathrm{C}}+Q_{\mathrm{R}}}$	$I_{\mathrm{AC}} = \tilde{F}(\mathrm{z})$	$I_{\mathrm{A}} = I_{\mathrm{AC}} \cdot \mathrm{\alpha} + I_{\mathrm{AS}} \cdot (1-\alpha)$		
	$z = f(Q) = \frac{Q'_{\mathrm{C}}+Q_{\mathrm{R}}}{Q_{\mathrm{MIN}}}$	$I_{\mathrm{AS}} = -\tilde{F}(\mathrm{z})$			

$^{*}Q\acute{}_{\mathrm{C}} = 0$ means the complete substitution of current (fresh)water source with WWTP effluent.

and (ii) the availability (*A*) of sources (i.e. water volumes), that have to be assessed with respect to (1) the current situation (*C*) and (2) a standard condition (*S*).

Table 2, again, lists the mathematical formulations for normalization (graphically displayed in S5 of Supporting information) and rating curves, and the following paragraphs illustrate their use.

2.2.3.1. Quality index. In this case, the normalization takes place with respect to the concentration of pollutants in the present source (for the current situation) and the index $I_{\mathrm{QC,i}}$ is calculated by means of Eq. (1); on the contrary, for the standard condition, a comparison with the maximum allowable concentration for reuse was applied, and the index $I_{\mathrm{QS,i}}$ is calculated by means of Eq. (1), as well.

In particular, the crucial variables for z curves are as follows:

- x_{C}, that is, the concentration of the *i*th parameter in the water currently used;
- x_{R}, that is, the concentration of the *i*th parameter in the reused water: It can be either a mixture of the WWTP effluent with freshwater taken from other sources or the WWTP effluent alone. x_{R} is calculated based on the volumetric ratio between waste- and freshwater:

$X_{\mathrm{R}} = (x_{\mathrm{C}} \cdot Q'_{\mathrm{C}} + x_{\mathrm{EFF}} \cdot Q_{\mathrm{R}})/(Q'_{\mathrm{C}} + Q_{\mathrm{r}})$, where $Q'_{\mathrm{C}}+ Q_{\mathrm{R}}$ is explained hereinafter;

- x_{MAX}, that is, the maximum allowable value of the *i*th parameter for the examined application (for instance, in case of agricultural reuse in Italy, the concentrations reported in M.D. 185/2003).

The average weighted over each "i" parameter (by means of the pollutant-specific weights, w_i) allows the calculation of I_{QC} and I_{QS}; and the weighted average of the 2 indices (by means of a case-specific coefficient, α) provides the overall quality index, I_{Q}.

2.2.3.2. Availability index. In this case, the normalization is based on the present (fresh)water quantity (for the current situation) and the index I_{AC} is calculated by means of Eq. (1); on the contrary, for the standard condition, a comparison with the actual water needs was applied, and the index I_{AS} is calculated by means of Eq. (1) as well, reversed in sign: Physically, it means that the maximum benefit ($I = +1$) starts with a water availability around two times more than water requirement (i.e. from $z = 2$).

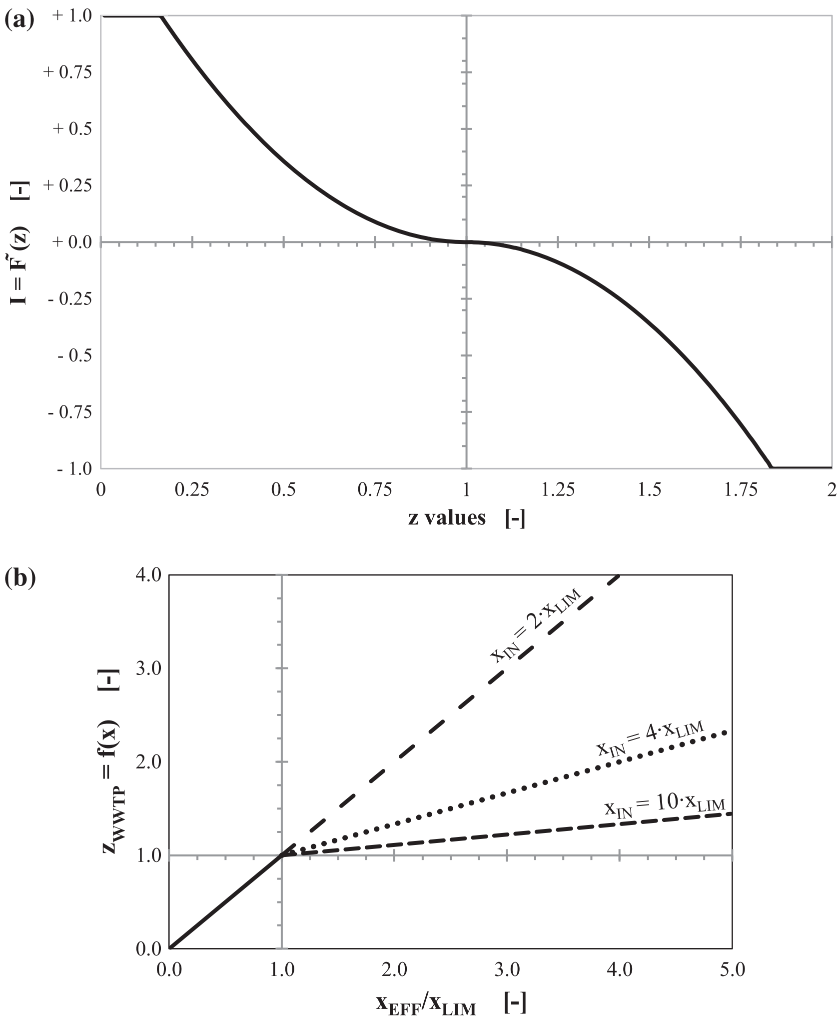

Fig. 2. (a) Graphical representation of the rating curve for indices calculation (Eq. (1)) and (b) normalization curve for WWTP (as a function of effluent/limit concentrations ratio, for different inlet concentrations).

In particular, the crucial variables for z curves are as follows:

- Q_C, that is, the currently available flow rate of (fresh) water;
- Q'_C, that is, the flow rate of the current supply source that would be used also under reuse hypothesis ($0 \leq Q'_C \leq Q_C$);
- Q_R, that is, the WWTP effluent flow rate subject to reuse. $Q'_C + Q_R$ represents the overall flow rate available in case of reclamation;
- Q_{MIN}, that is, the minimum flow rate which satisfies water requirements (e.g. for crops).

The weighted average of the 2 indices (by means of the case-specific coefficient α, again) provides the availability index, I_A.

2.3. The final evaluation

The final evaluation F is a synthetic numerical value that is determined by a weighted average of all indices I contributing to the assessment of the actors: Then F varies from +1 (best performance) to −1 (worst performance).

As reported in Table 2, a, weighted average allows the calculation of the final evaluation for WWTP, F_{WWTP}: $\sum I_{WWTP,i} \cdot w_i$, where w_i are the pollutant-specific weights, and for the final user, F_u: $I_Q \cdot \beta + I_A \cdot (1 - \beta)$, by means of a case-specific coefficient (β).

On the contrary, the final result of hydraulic system F_{HS} is a Boolean variable (YES/NO answer) based on an economic comparison: If costs for reuse are lower than the current situation, then F_{HS} is equal to +1, otherwise $F_{HS} = -1$. For this actor, it has been decided not to apply a rating function: Indeed, affordability is a fundamental constraint to investments in a “limited-resources” sector such as water management, and an economic disadvantage (even small) could determine the failure to implement an infrastructure.

In this way, the overall judgment on the feasibility of reuse can be finally drawn as the average of the single ratings calculated for each actor (F_{WWTP}, F_{HS}, and F_{u}): Therefore, values greater than zero indicate the suitability of such a practice, even if an adverse assessment can arise also if at least one of the three actors expresses some critical issues ($F < 0$).

2.4. DSS validation

The proposed model was validated through the application to several case studies: Ten Italian plants were investigated, differing in terms of

- reuse status: already practiced vs. under study;
- WWTP characteristics: size, polishing treatments, and reused/reusable flow rate;
- current water availability;
- reuse scenario (either agricultural or industrial applications);
- geographical location.

The characteristics of each WWTP and the numerical ranks obtained with the model are summarized in Table 3: It clearly evidences strengths and weaknesses of each part, namely +1 for a complete success and −1 for failure, and the final synthesis process among the 3 actors.

The entire study on ten WWTPs is reported in [20], while in this paper, two of them (#1 and #2 WWTP, actual and possible reuse in agriculture, respectively) were selected as examples for DSS explanation.

3. Results and discussion

3.1. #1 WWTP

The first case study (scenario: agricultural reuse already practiced) was a municipal WWTP (design size 200,000 P.E., flow rate: 40,000 m^3/d) located in the Po valley (northern Italy): It is a conventional activated sludge system with pre-denitrification, equipped with tertiary filtration and UV disinfection (plant scheme reported in S6 of Supporting information).

The DSS application (by way of example, the numerical illustration of indices calculation for COD, $I_{\text{WWTP,COD}}$, $I_{\text{QC,COD}}$, and $I_{\text{QS,COD}}$ is reported in S7 of Supporting information) showed that

(1) WWTP reached good performances for all the 7 key parameters (as listed in Table 4), leading to a strongly positive final evaluation ($F_{\text{WWTP}} = +0.52$). Moreover, the additional analyses (i) highlighted plant reliability, with indices higher than zero for almost all the scores calculated with extreme values (75th and 95th percentile, and maximum displayed in Fig. 3(a), in addition to the average); and (ii) confirmed the positive judgment also with the addition of optional parameters (SAR and EC: see S2 of Supporting information).

(2) For the hydraulic system (a 3,800-m long pipeline installed to convey by gravity the effluent to the irrigation network), the investment costs were totally covered by an external funding (both local and European financing), and O&M costs (1.1 €cent/$m^3 \equiv I_{\text{HS}}$) resulted lower than the current cost for freshwater supply (4.9 €cent/m^3): Therefore, the economic sustainability was satisfied and F_{HS} set to +1.

(3) Final user. The results of water quality assessment are reported in Table 4: Mixed flow (fresh Q'_{C} + WWTP effluent Q_{R}) was characterized by a low level of contamination, complying with Italian regulatory standards for water reclamation ($I_{\text{QS}} = +0.48$), except for TSS, and *E. coli*; moreover, the reuse of WWTP effluent improved water quality compared to the current source alone ($I_{\text{QC}} = +0.26$, mainly due to BOD_5, NH_4^+, TSS and *E. coli*). The evaluation on this issue is then clearly positive, as underlined by the numerical value of I_{Q} (+0.37). Additional parameters (SAR, EC, and others: see S2 of Supporting information) were also assessed, showing only slight variations in model outputs. For the calculation, the hypotheses of equal importance for each key pollutant ($w_{\text{i}} = 1/7$, so as not to assign a different role to single parameters) and for current/standard comparison ($\alpha = 0.5$) were taken. As the availability regarded, water needs for crops (300 L/s) would be not satisfied by the freshwater source alone (150 L/s), while WWTP effluent (500 L/s average flow rate) was able to achieve this target. As result, the comparison with both the current situation and the standard condition evidenced maximum benefits ($I_{\text{AC}} = I_{\text{AS}} = +1 \rightarrow I_{\text{A}} = +1$). Accordingly, the calculated global score for the final user was definitely positive ($F_{\text{u}} = +0.69$, calculated assuming equal importance for quality and

Table 3
List of investigated WWTPs, together with main characteristics and outcomes of DSS application; arrows indicate the final judgment on reuse feasibility: positive (≥0.5), neutral (0 – 0.5), or negative (≤0)

	Features					Indices									
							Hydr.	Final user							
Analyzed WWTP	Reuse status	Polishing treatments	Q_{reuse} (m^3/d)	Water availability	Reuse scenario	WWTP F_{WWTP}	Syst. F_{HS}	I_{QC}	I_{QS}	I_Q	I_{AC}	I_{AS}	I_A	F_u	Overall judgment
# 1	Practiced	Filtration + disinfection (UV)	25,000	Scarce	Agricultural	+0.52	+1	+0.26	+0.48	+0.37	+1	+1	+1	+0.69	+0.74 ⬆
# 2	Under study	Filtration + disinfection (O_3)	30,000	Good (surface)	Agricultural	+0.19	+1	−0.72	+0.19	−0.27	+0.07	+1	+0.54	+0.14	+0.44 ➡
# 3	Practiced	Filtration + disinfection (UV)	20,000	Scarce	Agricultural	+0.5	+1	−0.13	+0.5	+0.19	+0	+0	+0	+0.09	+0.53 ⬆
# 4	Under study	Coagulation/flocculation + filtration + disinfection	30,000	Scarce	Agricultural	+0.42	−1	−0.2	+0.19	−0.01	+1	+0.06	+0.53	+0.27	−0.11 ⬇
# 5	Practiced	Filtration + disinfection (O_3)	6,000	Scarce	Industrial	+0.41	+1	n.a.	+0.41	+0.41	+0	+0	+0	+0.21	+0.54 ⬆
# 6	Under study	Filtration + disinfection (UV)	30,000	Good (surface)	Agricultural	+0.36	+1	−0.05	+0.13	+0.04	+0	+0	+0	+0.02	+0.46 ➡
# 7	Practiced	Physical/chemical + biological	5,000	Scarce	Agricultural	+0.51	+1	+0.5	+0.5	+0.5	+1	+0	+0.5	+0.5	+0.67 ⬆
# 8	Under study	Filtration + disinfection (UV)	120,000	Good (surface)	Agricultural	+0.38	+1	−0.01	+0.83	+0.41	+0.01	+0.01	+0.01	+0.22	+0.53 ⬆
# 9	Practiced	Coagulation/flocculation + filtration + disinfection	5,000	Scarce	Industrial	+0.48	+1	n.a.	+0.48	+0.48	+1	+0	+0.5	+0.49	+0.66 ⬆
# 10	Under study	Absent	35,000	Scarce	Agricultural	+0.55	−1	−0.86	+0.42	−0.22	+1	+0.08	+0.54	+0.16	−0.1 ⬇

Table 4
Results of # 1 WWTP. indices calculation for WWTP (F_{WWTP}) and final user (water quality, I_Q) referred to 7 mandatory key parameters

	$I_{WWTP,i}$	$I_{QC,i}$	$I_{QS,i}$
BOD_5	+1	+0.31	+1
COD	+0.75	−0.002	+0.79
NH_4^+	+1	+0.37	+0.93
N_{tot}	+0.19	−0.11	+0.27
P_{tot}	+0.48	−0.07	+0.58
TSS	+0.13	+0.79	−0.10
E. coli	+0.05	+0.51	−0.10
	$F_{WWTP} = +0.52$	$I_{QC} = +0.26$ $I_Q = +0.37$	$I_{QS} = +0.48$

availability issues: $\beta = 0.5$), thus indicating that final user markedly benefits from this practice.

In conclusion, each of the three actors obtained an optimal ranking, which determined an overall judgment clearly in favor of wastewater reuse (+0.74): Indeed, here, this practice has been already adopted for many years.

3.2. #2 WWTP

The second case study (scenario: agricultural reuse under study) was a municipal WWTP (design size 100,000 P.E., flow rate: 30,000 m^3/d) located near Milan (northern Italy): It is a conventional activated sludge system with pre-denitrification, equipped with tertiary filtration and O_3 disinfection (plant scheme reported in S8 of Supporting Information).

The DSS application showed that

1. WWTP reached sufficient performances ($F_{WWTP} = +0.19$), even if ammonia and *E. coli* represented critical parameters (as highlighted in Table 5). Moreover, the additional analyses showed the unreliability of effluent quality: For instance, all the indices calculated with the 95th percentile of concentrations turned out to be lower than zero (Fig. 3(b)).
2. For the hydraulic system (design: a pumping station, 3 m head, and a 490-m long pipeline), the costs to convey the effluent to the irrigation network ($I_{HS} = 1.5$ €cent/m^3, I + O&M) would be lower than the current cost for freshwater supply (3.8 €cent/m^3): Therefore, also in this case, the economic sustainability was satisfied and F_{HS} set to +1.
3. Final user. The results of water quality assessment are reported in Table 5: Reused flow (in this case, the use of WWTP effluent alone not diluted with freshwater is planned) had a much poorer quality in comparison with current freshwater source ($I_{QC} = -0.72$); nevertheless, Italian standards for wastewater reuse are almost totally complied with, being $I_{QS} = +0.19$, and coinciding with F_{WWTP} as expected under the hypothesis of complete substitution of freshwater source. Thus, the evaluation on this issue was barely negative ($I_Q = -0.26$). As previously set, equal

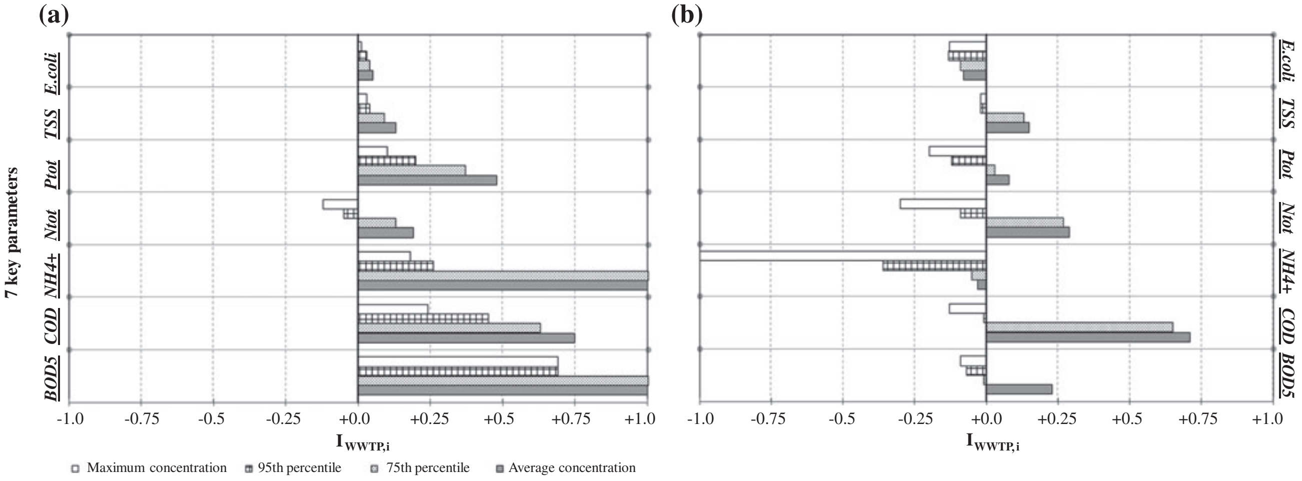

Fig. 3. Model outputs for WWTP actor: indices determination for the 7 key parameters, related to both typical (average concentrations) and extreme (75th and 95th percentile, and maximum concentrations) values. (a) #1 WWTP; (b) #2 WWTP.

Table 5
Results of # 2 WWTP. indices calculation for WWTP (F_{WWTP}) and final user (water quality, I_Q), referred to 7 mandatory key parameters

	$I_{WWTP,i}$	$I_{QC,i}$	$I_{QS,i}$
BOD_5	+0.23	−1	+0.23
COD	+0.71	−1	+0.71
NH_4^+	−0.03	−1	−0.03
N_{tot}	+0.29	−1	+0.29
P_{tot}	+0.08	−1	+0.08
TSS	+0.15	−0.19	+0.15
E. coli	−0.08	+0.17	−0.08
	$F_{WWTP} = +0.19$	$I_{QC} = -0.72$ $I_Q = -0.26$	$I_{QS} = +0.19$

importance to each key pollutant ($w_i = 1/7$) and to current/standard comparison ($\alpha = 0.5$) was assigned. Water availability, on the contrary, was not a crucial factor: WWTP effluent (350 L/s average flow rate) would be enough to plenty satisfy water needs for crops (75 L/s), thus leading to $I_{AS} = +1$, and the discharge was slightly higher than the actual freshwater source (300 L/s), that is, $I_{AS} = +0.07$. As a result, the evaluation on this issue was plainly positive ($I_A = +0.53$). Therefore, the calculated global score for the final user was barely sufficient ($F_u = +0.13$, calculated again assuming equal importance for quality and availability issues: $\beta = 0.5$).

In conclusion, even if the overall judgment was higher than zero (+0.44), the critical issues revealed by 2 actors (WWTP and final user) have represented significant barriers to the implementation of this practice, being suitability conditions not completely satisfied.

3.2.1. DSS flexibility and significance of weights

The weights of each part of the model can be also changed according to specific peculiarities: This flexibility allows the expert to better fit the DSS findings to each case study; for instance, if the social acceptance was a critical factor, it would be reflected in an increase of β value; on the contrary, if the critical factor was represented by water availability, β should be reduced.

For instance, #2 WWTP evidenced that if social acceptance is the main driver for the final user (thus leading to a value of β equal to 1), the overall judgment gets worse (=0.30); on the contrary, if the final user index is based only on water availability ($\beta = 0$), a positive judgment of 0.60 is reached. S3 in Supporting Information graphically summarizes this behavior. A similar analysis could be carried out also with the other weights, w_i and α.

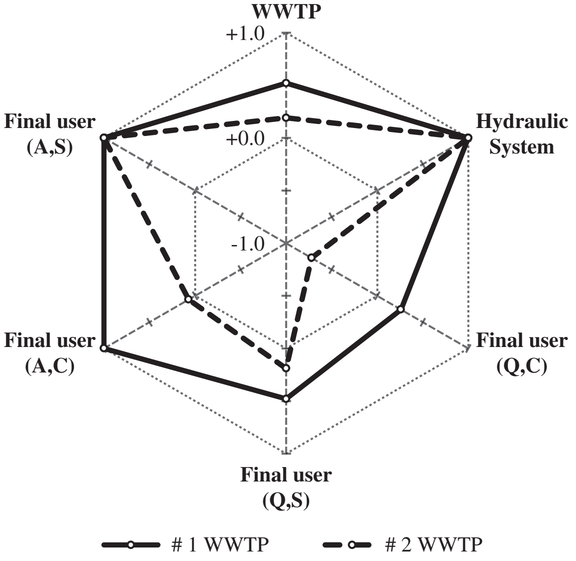

Fig. 4. Radar chart summarizing strengths and weaknesses of the reclamation process actors (solid line: #1 WWTP; dotted line: #2 WWTP).

4. Conclusions

In this work, an innovative DSS was built up as a tool to judge wastewater reuse feasibility. Both technical and economic parameters were included in the model, and the three actors of the process were taken into account: the WWTP, the hydraulic conveying system, and the final user. The conceptual framework was based on (i) definition of specific input factors for each actor, (ii) calculation of numerical indices by means of appropriate functions (normalization and rating curves), and (iii) determination of final evaluations.

Its application to ten case studies revealed model ability to assess complex situations, where several factors have to be simultaneously considered, and to achieve synthetic but comprehensive judgments, for a fast identification of main strengths and weaknesses of assessed reuse scenario. For instance, the radar chart of Fig. 4 (referring to 2 described plants; similar charts are presented for all the analyzed WWTPs in S9 of Supporting information) resumes the final judgment for each actor and emphasizes that #1 WWTP was much more suitable for reuse than #2, that displayed significant shortcomings for the actor “final user” (the effluent quality compared to the current source gave a strong negative index).

If, from the one hand, synthetic numerical values can darken detailed information about single issues, from the other hand, a final score can provide quick and unbiased answers, representing an effective help in decision-making processes if used by an expert: The DSS is designed to make data processing and findings systematic; then, it is up of an expert to critically interpret the final judgment, also with a modification of model ingredients according to case-specific peculiarities. Indeed, a further strength lies in flexibility of proposed DSS: It is capable to easily change the weight of parameters and/or to add others, according to site-specific conditions/requirements (e.g. new regulatory references).

In conclusion, as general and wider outcomes, the proposed work can complement the existing knowledge/model currently used for wastewater reuse assessment, thanks to its integrated perspective (WWTP + hydraulic system + final user) and easy-to-handle answers. In particular, the DSS fits into the debate still open within the European Commission on how to regulate wastewater reuse, to provide an institutional framework: DSS application, therefore, may represent a useful tool for this achievement.

Acknowledgements

Authors would like to thank ISPRA (the Italian Environment Protection Agency), for funding this research and, in particular, Carlo Ottavi and Silvia Pietra for their valuable technical contribution. Additional thanks to Sergio Papiri, Carlo Collivignarelli, Fausta Prandini, and Renato Corradini for their help and to the management staff of analyzed Italian WWTPs: Cremona; Locate Triulzi (Milan); Alghero (Sassari); Acqua dei Corsari (Palermo); Baciacavallo (Prato); Fregene (Rome); Fasano (Brindisi); Peschiera del Garda (Verona); Stintino (Sassari); Udine.

Authoring: M. Papa and G. Bertanza planned DSS conceptual framework and carried out paper drafting; A. Abbà carried out indices elaborations; and G. Bertanza coordinated the research.

Supplemental data

Supplemental data for this article can be accessed here: http://dx.doi.10.1080/19443994.2015.1029532.

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